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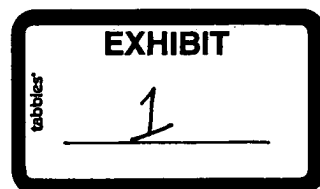
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Specification and Drawings, as originally filed, with Application for Patent Serial No:
2,274,240, on June 10, 1999, by **QUESTOR INDUSTRIES INC.**, assignee of
Bowie G. Keefer, Christopher McLean and Michael J. Brown, for "Electrical Current
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ABSTRACT

In one embodiment, an electrical current generating system consists of a fuel cell, and an oxygen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet for receiving a supply of hydrogen gas, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The electrical current generating system also includes gas recirculation means coupled to the cathode gas outlet for recirculating a portion of cathode exhaust gas exhausted from the cathode gas outlet to the cathode gas inlet. In another embodiment, an electrical current generating system consists of a fuel cell, an oxygen gas delivery system, and a hydrogen gas delivery system. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The hydrogen gas delivery system includes a hydrogen gas inlet for receiving a first hydrogen gas feed from the anode gas outlet, and a hydrogen gas outlet coupled to the anode gas inlet for delivering hydrogen gas to the anode channel with increased purity from the first hydrogen gas feed.

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ELECTRICAL CURRENT GENERATION SYSTEM

FIELD OF THE INVENTION

5 The present invention relates to a fuel cell for the generation of electrical current. In particular, the present invention relates to a fuel cell-based electrical generation system which employs pressure swing adsorption for enhancing the efficiency of the fuel cell.

10 BACKGROUND OF THE INVENTION

 Fuel cells provide an environmentally friendly source of electrical current. One form of fuel cell used for generating electrical power includes an anode for receiving hydrogen gas, a cathode for receiving oxygen gas, and an alkaline electrolyte. Another form of fuel cell includes an anode channel for receiving a flow of hydrogen gas, a
15 cathode channel for receiving a flow of oxygen gas, and a polymer electrolyte membrane (PEM) which separates the anode channel from the cathode channel. In both instances, oxygen gas which enters the cathode reacts with hydrogen ions which cross the electrolyte to generate a flow of electrons. Environmentally safe water vapour is also produced as a byproduct. However, several factors have limited the widespread use of
20 fuel cells as power generation systems.

 Firstly, in order to extract a continuous source of electrical power from the fuel cell, it is necessary to provide the fuel cell with a continuous source of oxygen and hydrogen gas. However, with atmospheric air as the direct source of oxygen to the
25 cathode channel, performance of PEM fuel cells is severely impaired by the low partial pressure of oxygen and the concentration polarization of nitrogen, while alkaline fuel cells require a pretreatment purification system to remove carbon dioxide from the feed air. Further, as the average oxygen concentration in a cathode channel with atmospheric air feed is typically only about 15%, the size of the fuel cell must be undesirably large in

order to provide sufficient power for industrial applications.

In order to achieve a partial pressure of oxygen through the cathode channel sufficient for the attainment of competitive current densities from a PEM fuel cell system, particularly for vehicular propulsion, it is necessary to compress the air feed to at least 3 atmospheres before the air feed is introduced to the cathode channel. As will be appreciated, the power input necessary to sufficiently compress the air feed reduces the overall efficiency of the fuel cell system. It has been proposed to use polymeric membranes to enrich the oxygen, but such membranes actually reduce the oxygen partial pressure and the reduction in total pressure more than offsets the limited enrichment attainable.

Secondly, external production, purification, dispensing and storage of hydrogen (either as compressed gas or cryogenic liquid) requires costly infrastructure, while storage of hydrogen fuel on vehicles presents considerable technical and economic barriers. Accordingly, for stationary power generation, it is preferred to generate hydrogen from natural gas by steam reforming or partial oxidation followed by water gas shift. For fuel cell vehicles using a liquid fuel, it is preferred to generate hydrogen from methanol by steam reforming or from gasoline by partial oxidation or autothermal reforming, again followed by water gas shift. However, the resulting hydrogen contains carbon monoxide and carbon dioxide impurities which cannot be tolerated respectively by the PEM fuel cell catalytic electrodes and the alkaline fuel cell electrolyte in more than trace levels.

The conventional method of removing residual carbon monoxide from the hydrogen feed to PEM fuel cells has been catalytic selective oxidation, which compromises efficiency as both the carbon monoxide and a fraction of the hydrogen are consumed by low temperature oxidation, without any recovery of the heat of combustion. Palladium diffusion membranes can be used for hydrogen purification, but have the disadvantages of delivery of the purified hydrogen at low pressure, and also the use of

rare and costly materials.

Thirdly, pressure swing adsorption systems (PSA) have the attractive features of being able to provide continuous sources of oxygen and hydrogen gas, without significant
5 contaminant levels. PSA systems and vacuum pressure swing adsorption systems (vacuum-PSA) separate gas fractions from a gas mixture by coordinating pressure cycling and flow reversals over an adsorbent bed which preferentially adsorbs a more readily
adsorbed gas component relative to a less readily adsorbed gas component of the mixture. The total pressure of the gas mixture in the adsorbent bed is elevated while the
10 gas mixture is flowing through the adsorbent bed from a first end to a second end thereof, and is reduced while the gas mixture is flowing through the adsorbent from the second end back to the first end. As the PSA cycle is repeated, the less readily adsorbed
component is concentrated adjacent the second end of the adsorbent bed, while the more readily adsorbed component is concentrated adjacent the first end of the adsorbent bed.
15 As a result, a "light" product (a gas fraction depleted in the more readily adsorbed component and enriched in the less readily adsorbed component) is delivered from the second end of the bed, and a "heavy" product (a gas fraction enriched in the more
strongly adsorbed component) is exhausted from the first end of the bed.

20 However, the conventional system for implementing pressure swing adsorption or vacuum pressure swing adsorption uses two or more stationary adsorbent beds in parallel, with directional valving at each end of each adsorbent bed to connect the beds in
alternating sequence to pressure sources and sinks. This system is often difficult and expensive to implement due to the complexity of the valving required.

25

Further, the conventional PSA system makes inefficient use of applied energy, because feed gas pressurization is provided by a compressor whose delivery pressure is the highest pressure of the cycle. In PSA, energy expended in compressing the feed gas used for pressurization is then dissipated in throttling over valves over the instantaneous

pressure difference between the adsorber and the high pressure supply. Similarly, in vacuum-PSA, where the lower pressure of the cycle is established by a vacuum pump exhausting gas at that pressure, energy is dissipated in throttling over valves during countercurrent blowdown of adsorbers whose pressure is being reduced. A further energy
5 dissipation in both systems occurs in throttling of light reflux gas used for purge, equalization, cocurrent blowdown and product pressurization or backfill steps. These energy sinks reduce the overall efficiency of the fuel cell system. Accordingly, there remains a need for an efficient fuel cell-based electrical generation system which can produce sufficient power for industrial applications.

10

SUMMARY OF THE INVENTION

According to the invention, there is provided a fuel cell-based electrical generation system which addresses the deficiencies of the prior art fuel cell electrical
15 generation systems.

The electrical current generating system, according to a first embodiment of the present invention, comprises a fuel cell, and a oxygen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet for receiving a supply of hydrogen
20 gas, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel.

25 The electrical current generating system also includes gas recirculation means coupled to the cathode gas outlet for recirculating a portion of cathode exhaust gas exhausted from the cathode gas outlet to the cathode gas inlet.

In a preferred implementation of the first embodiment, the oxygen gas delivery

system comprises an oxygen gas separation system for separating oxygen gas from air. Preferably, the oxygen gas separating system comprises an oxygen pressure swing adsorption system including a rotary module having a stator and a rotor rotatable relative to the stator. The rotor includes a number of flow paths for receiving adsorbent material
5 therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component. The pressure swing adsorption system also includes compression machinery coupled to the rotary module for facilitating gas flow through the flow paths for separating the first gas component from the second gas component. The stator includes a first stator valve surface, a second stator
10 valve surface, and plurality of function compartments opening into the stator valve surfaces. The function compartments include a gas feed compartment, a light reflux exit compartment and a light reflux return compartment.

In one variation, the compression machinery comprises a compressor for
15 delivering pressurized air to the gas feed compartment, and a light reflux expander coupled between the light reflux exit compartment and the light reflux return compartment. The gas recirculating means comprises a compressor coupled to the light reflux expander for supplying oxygen gas, exhausted from the cathode gas outlet, under pressure to the cathode gas inlet. As a result, energy recovered from the pressure swing
20 adsorption system can be applied to boost the pressure of oxygen gas delivered to the cathode gas inlet.

In another variation, restrictor orifices are disposed between the light reflux exit compartment and the light reflux return compartment for pressure letdown in replacement
25 of the light reflux expander. The gas recirculating means comprises a compressor coupled to the cathode gas outlet for supplying oxygen gas to the cathode gas inlet, and a restrictive orifice disposed between the cathode gas outlet and the pressurization compartment for recycling a portion of the oxygen gas as feed to the pressure swing adsorption system. As a result, energy recovered from the cathode gas outlet can be used

to help pressurize the cathode gas inlet.

5 The electrical current generating system, according to a second embodiment of the present invention, comprises a fuel cell, an oxygen gas delivery system, and a hydrogen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet and an anode gas outlet, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel.

10 The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The hydrogen gas delivery system includes a hydrogen gas inlet for receiving a first hydrogen gas feed from the anode gas outlet, and a hydrogen gas outlet coupled to the anode gas inlet for delivering hydrogen gas to the anode channel with increased purity from the first hydrogen gas feed.

15 In a preferred implementation of the second embodiment, the oxygen gas separation system comprises an oxygen pressure swing adsorption system, and the hydrogen gas separation system comprises a reactor for producing a second hydrogen gas feed from hydrocarbon fuel, and a hydrogen pressure swing adsorption system coupled to the reactor for purifying hydrogen gas received from the first and second hydrogen gas feeds. Both pressure swing adsorption systems include a rotary module having a stator and a rotor rotatable relative to the stator. The rotor includes a number of flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component. The function compartments include a gas feed compartment and a heavy product compartment.

25 In one variation, the oxygen pressure swing adsorption system includes a compressor coupled to the gas feed compartment for delivering pressurized air to the gas

feed compartment, and a vacuum pump coupled to the compressor for extracting nitrogen product gas from the heavy product compartment. The reactor comprises a steam reformer, including a burner, for producing syngas, and a water gas shift reactor coupled to the steam reformer for converting the syngas to the second hydrogen gas feed. The
5 hydrogen pressure swing adsorption system includes a vacuum pump for delivering fuel gas from the heavy product compartment to the burner. The fuel gas is burned in the burner, and the heat generated therefrom is used to supply the endothermic heat of reaction necessary for the steam reformer reaction. The resulting syngas is delivered to the water gas shift reactor for removal of impurities, and then delivered as the second
10 hydrogen gas feed to the hydrogen pressure swing adsorption system.

In another variation, the invention includes a burner for burning fuel. The reactor comprises an autothermal reformer for producing syngas, and a water gas shift reactor coupled to the autothermal reformer for converting the syngas to the second hydrogen gas
15 feed. The compressor of the oxygen pressure swing adsorption system delivers pressurized air to the burner, and the heavy product gas is delivered from the hydrogen pressure swing adsorption system as tail gas to be burned in the burner. The compression machine of the oxygen pressure swing adsorption system also includes an expander coupled to the compressor for driving the compressor from hot gas of combustion emitted
20 from the burner.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiment of the present invention will now be described, by way
25 of example only, with reference to the drawings, in which:

Fig. 1 is a sectional view of a rotary PSA module suitable for use with the present invention, showing the stator and rotor situated in the stator;

Fig. 2 is a sectional view of the module of Fig. 1, with the stator deleted for clarity;

Fig. 3 is a sectional view of the stator shown in Fig. 1, with the rotor deleted for
5 clarity;

Fig. 4 is an axial section of the module of Fig. 1;

Fig. 5 shows a typical PSA cycle attainable with the PSA system shown in Figs. 1
10 to 4;

Fig. 6 shows one variation of the PSA cycle with heavy reflux, attainable with the PSA system shown in Figs. 1 to 4;

15 Fig. 7 shows a pressure swing adsorption apparatus for separating oxygen gas from air, suitable for use with the present invention, and depicting the rotary module shown in Fig. 1 and a compression machine coupled to the rotary module;

20 Fig. 8 shows a pressure swing adsorption apparatus for separating hydrogen gas from refinery feed gas, suitable for use with the present invention, and depicting the rotary module shown in Fig. 1 and a compression machine coupled to the rotary module;

25 Fig. 9 shows an electrical current generating system, according to a first embodiment of the present invention, including an oxygen-separating PSA system for supplying enriched oxygen to the fuel cell cathode channel with energy recovery from light reflux expansion to boost the pressure of oxygen circulating in the fuel cell cathode loop;

Fig. 10 shows a first variation of the electrical current generating system shown in

Fig. 9, but with the PSA system including a countercurrent blowdown expander driving a free rotor exhaust vacuum pump for vacuum-PSA operation;

Fig. 11 shows a second variation of the electrical current generating system shown in Fig. 9, with a portion of the oxygen enriched gas discharged from the fuel cell cathode being used for a pressurization step for the PSA system;

Fig. 12 shows an electrical current generating system, according to a second embodiment of the present invention, including an oxygen-separating PSA system for supplying enriched oxygen to the fuel cell cathode channel, and a hydrogen-separating PSA system for supplying enriched hydrogen to the fuel cell anode channel, with the hydrogen-separating PSA system receiving feed gas from a steam reformer; and

Fig. 13 shows an electrical current generating system, according to a variation of the electrical current generating system shown in Fig. 12, but with the hydrogen-separating PSA system receiving feed gas from an autothermal reformer.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

To aid in understanding the present invention, a pressure swing adsorption process and associated apparatus, suitable for use with the present invention, will be described first, with reference to Figs. 1 through 6. Thereafter, an oxygen-separating pressure swing adsorption system and a hydrogen-separating pressure swing adsorption system will be described with reference to Figs. 7 and 8 respectively. Two embodiments of the invention, together with variations thereon, will then be described commencing with Fig. 9.

Figs. 1, 2, 3 and 4

A rotary module 10 which is suitable for use as part of the present invention is

shown in Figs. 1, 2, 3 and 4. The module includes a rotor 11 revolving about axis 12 in the direction shown by arrow 13 within stator 14. However, it should be understood that the invention is not limited to PSA systems having rotary modules. Rather other arrangements may be employed without departing from the scope of the invention. For instance, if desired, the present invention may be employed with multiple stationary adsorbent beds in parallel, with directional valving at each end of each adsorbent bed to connect the beds in alternating sequence to pressure sources and sinks.

In general, the rotary module 10 may be configured for flow through the adsorber elements in the radial, axial or oblique conical directions relative to the rotor axis. For operation at high cycle frequency, radial flow has the advantage that the centripetal acceleration will lie parallel to the flow path for most favourable stabilization of buoyancy-driven free convection, as well as centrifugal clamping of granular adsorbent with uniform flow distribution.

As shown in Fig. 2, the rotor 11 is of annular section, having concentrically to axis 12 an outer cylindrical wall 20 whose external surface is first valve surface 21, and an inner cylindrical wall 22 whose internal surface is second valve surface 23. The rotor has (in the plane of the section defined by arrows 15 and 16 in Fig. 4) a total of "N" radial flow adsorber elements 24. An adjacent pair of adsorber elements 25 and 26 are separated by partition 27 which is structurally and sealingly joined to outer wall 20 and inner wall 22. Adjacent adsorber elements 25 and 26 are angularly spaced relative to axis 12 by an angle of $[360^\circ / N]$.

Adsorber element 24 has a first end 30 defined by support screen 31 and a second end 32 defined by support screen 33. The adsorber may be provided as granular adsorbent, whose packing voidage defines a flow path contacting the adsorbent between the first and second ends of the adsorber.

First aperture or orifice 34 provides flow communication from first valve surface 21 through wall 20 to the first end 30 of adsorber 24. Second aperture or orifice 35 provides flow communication from second valve surface 23 through wall 22 to the second end 31 of adsorber 24. Support screens 31 and 33 respectively provide flow distribution 32 between first aperture 34 and first end 30, and between second aperture 35 and second end 32, of adsorber element 24. Support screen 31 also supports the centrifugal force loading of the adsorbent.

As shown in Fig. 3, stator 14 is a pressure housing including an outer cylindrical shell or first valve stator 40 outside the annular rotor 11, and an inner cylindrical shell or second valve stator 41 inside the annular rotor 11. Outer shell 40 carries axially extending strip seals (e.g. 42 and 43) sealingly engaged with first valve surface 21, while inner shell 41 carries axially extending strip seals (e.g. 44 and 45) sealingly engaged with second valve surface 23. The azimuthal sealing width of the strip seals is greater than the diameters or azimuthal widths of the first and second apertures 34 and 35 opening through the first and second valve surfaces.

A set of first compartments in the outer shell each open in an angular sector to the first valve surface, and each provide fluid communication between its angular sector of the first valve surface and a manifold external to the module. The angular sectors of the compartments are much wider than the angular separation of the adsorber elements. The first compartments are separated on the first sealing surface by the strip seals (e.g. 42). Proceeding clockwise in Fig. 3, in the direction of rotor rotation, a first feed pressurization compartment 46 communicates by conduit 47 to first feed pressurization manifold 48, which is maintained at a first intermediate feed pressure. Similarly, a second feed pressurization compartment 50 communicates to second feed pressurization manifold 51, which is maintained at a second intermediate feed pressure higher than the first intermediate feed pressure but less than the higher working pressure.

For greater generality, module 10 is shown with provision for sequential admission of two feed mixtures, the first feed gas having a lower concentration of the more readily adsorbed component relative to the second feed gas. First feed compartment 52 communicates to first feed manifold 53, which is maintained at substantially the higher working pressure. Likewise, second feed compartment 54 communicates to second feed manifold 55, which is maintained at substantially the higher working pressure. A first countercurrent blowdown compartment 56 communicates to first countercurrent blowdown manifold 57, which is maintained at a first countercurrent blowdown intermediate pressure. A second countercurrent blowdown compartment 58 communicates to second countercurrent blowdown manifold 59, which is maintained at a second countercurrent blowdown intermediate pressure above the lower working pressure. A heavy product compartment 60 communicates to heavy product exhaust manifold 61 which is maintained at substantially the lower working pressure. It will be noted that compartment 58 is bounded by strip seals 42 and 43, and similarly all the compartments are bounded and mutually isolated by strip seals.

A set of second compartments in the inner shell each open in an angular sector to the second valve surface, and each provide fluid communication between its angular sector of the second valve surface and a manifold external to the module. The second compartments are separated on the second sealing surface by the strip seals (e.g. 44). Proceeding clockwise in Fig. 3, again in the direction of rotor rotation, light product compartment 70 communicates to light product manifold 71, and receives light product gas at substantially the higher working pressure, less frictional pressure drops through the adsorbers and the first and second orifices. According to the angular extension of compartment 70 relative to compartments 52 and 54, the light product may be obtained only from adsorbers simultaneously receiving the first feed gas from compartment 52, or from adsorbers receiving both the first and second feed gases.

A first light reflux exit compartment 72 communicates to first light reflux exit

manifold 73, which is maintained at a first light reflux exit pressure, here substantially the higher working pressure less frictional pressure drops. A first cocurrent blowdown compartment 74 (which is actually the second light reflux exit compartment), communicates to second light reflux exit manifold 75, which is maintained at a first
5 cocurrent blowdown pressure less than the higher working pressure. A second cocurrent blowdown compartment or third light reflux exit compartment 76 communicates to third light reflux exit manifold 77, which is maintained at a second cocurrent blowdown pressure less than the first cocurrent blowdown pressure. A third cocurrent blowdown compartment or fourth light reflux exit compartment 78 communicates to fourth light
10 reflux exit manifold 79, which is maintained at a third cocurrent blowdown pressure less than the second cocurrent blowdown pressure.

A purge compartment 80 communicates to a fourth light reflux return manifold 81, which supplies the fourth light reflux gas which has been expanded from the third
15 cocurrent blowdown pressure to substantially the lower working pressure with an allowance for frictional pressure drops. The ordering of light reflux pressurization steps is inverted from the ordering of light reflux exit or cocurrent blowdown steps, so as to maintain a desirable "last out - first in" stratification of light reflux gas packets. Hence a first light reflux pressurization compartment 82 communicates to a third light reflux
20 return manifold 83, which supplies the third light reflux gas which has been expanded from the second cocurrent blowdown pressure to a first light reflux pressurization pressure greater than the lower working pressure. A second light reflux pressurization compartment 84 communicates to a second light reflux return manifold 85, which supplies the second light reflux gas which has been expanded from the first cocurrent
25 blowdown pressure to a second light reflux pressurization pressure greater than the first light reflux pressurization pressure. Finally, a third light reflux pressurization compartment 86 communicates to a first light reflux return manifold 87, which supplies the first light reflux gas which has been expanded from approximately the higher pressure to a third light reflux pressurization pressure greater than the second light reflux

pressurization pressure, and in this example less than the first feed pressurization pressure.

Additional details are shown in Fig. 4. Conduits 88 connect first compartment 60 to manifold 61, with multiple conduits providing for good axial flow distribution in compartment 60. Similarly, conduits 89 connect second compartment 80 to manifold 81. Stator 14 has base 90 with bearings 91 and 92. The annular rotor 11 is supported on end disc 93, whose shaft 94 is supported by bearings 91 and 92. Motor 95 is coupled to shaft 94 to drive rotor 11. The rotor could alternatively rotate as an annular drum, supported by rollers at several angular positions about its rim and also driven at its rim so that no shaft would be required. A rim drive could be provided by a ring gear attached to the rotor, or by a linear electromagnetic motor whose stator would engage an arc of the rim. Outer circumferential seals 96 seal the ends of outer strip seals 42 and the edges of first valve surface 21, while inner circumferential seals 97 seal the ends of inner strip seals 44 and the edges of second valve surface 23. Rotor 11 has access plug 98 between outer wall 20 and inner wall 22, which provides access for installation and removal of the adsorbent in adsorbers 24.

Figs. 5 and 6

Fig. 5 shows a typical PSA cycle which would be obtained using the foregoing gas separation system, while Fig. 6 shows a similar PSA cycle with heavy reflux recompression of a portion of the first product gas to provide a second feed gas to the process.

In Figs. 5 and 6, the vertical axis 150 indicates the working pressure in the adsorbers and the pressures in the first and second compartments. Pressure drops due to flow within the adsorber elements are neglected. The higher and lower working pressures are respectively indicated by dotted lines 151 and 152.

The horizontal axis 155 of Figs. 5 and 6 indicates time, with the PSA cycle period defined by the time interval between points 156 and 157. At times 156 and 157, the working pressure in a particular adsorber is pressure 158. Starting from time 156, the cycle for a particular adsorber (e.g. 24) begins as the first aperture 34 of that adsorber is opened to the first feed pressurization compartment 46, which is fed by first feed supply means 160 at the first intermediate feed pressure 161. The pressure in that adsorber rises from pressure 158 at time 157 to the first intermediate feed pressure 161. Proceeding ahead, first aperture passes over a seal strip, first closing adsorber 24 to compartment 46 and then opening it to second feed pressurization compartment 50 which is feed by second feed supply means 162 at the second intermediate feed pressure 163. The adsorber pressure rises to the second intermediate feed pressure.

First aperture 34 of adsorber 24 is opened next to first feed compartment 52, which is maintained at substantially the higher pressure by a third feed supply means 165. Once the adsorber pressure has risen to substantially the higher working pressure, its second aperture 35 (which has been closed to all second compartments since time 156) opens to light product compartment 70 and delivers light product 166.

In the cycle of Fig. 6, first aperture 34 of adsorber 24 is opened next to second feed compartment 54, also maintained at substantially the higher pressure by a fourth feed supply means 167. In general, the fourth feed supply means supplies a second feed gas, typically richer in the more readily adsorbed component than the first feed gas provided by the first, second and third feed supply means. In the specific cycle illustrated in Fig. 6, the fourth feed supply means 167 is a "heavy reflux" compressor, recompressing a portion of the heavy product back into the apparatus. In the cycle illustrated in Fig. 5, there is no fourth feed supply means, and compartment 54 could be eliminated or consolidated with compartment 52 extended over a wider angular arc of the stator.

While feed gas is still being supplied to the first end of adsorber 24 from either

compartment 52 or 54, the second end of adsorber 24 is closed to light product compartment 70 and opens to first light reflux exit compartment 72 while delivering "light reflux" gas (enriched in the less readily adsorbed component, similar to second product gas) to first light reflux pressure let-down means (or expander) 170. The first
5 aperture 34 of adsorber 24 is then closed to all first compartments, while the second aperture 35 is opened successively to (a) second light reflux exit compartment 74, dropping the adsorber pressure to the first cocurrent blowdown pressure 171 while delivering light reflux gas to second light reflux pressure letdown means 172, (b) third light reflux exit compartment 76, dropping the adsorber pressure to the second cocurrent
10 blowdown pressure 173 while delivering light reflux gas to third light reflux pressure letdown means 174, and (c) fourth light reflux exit compartment 78, dropping the adsorber pressure to the third cocurrent blowdown pressure 175 while delivering light reflux gas to fourth light reflux pressure letdown means 176. Second aperture 35 is then closed for an interval, until the light reflux return steps following the countercurrent
15 blowdown steps.

The light reflux pressure let-down means may be mechanical expanders or expansion stages for expansion energy recovery, or may be restrictor orifices or throttle valves for irreversible pressure let-down.

20

Either when the second aperture is closed after the final light reflux exit step (as shown in Figs. 5 and 6), or earlier while light reflux exit steps are still underway, first aperture 34 is opened to first countercurrent blowdown compartment 56, dropping the adsorber pressure to the first countercurrent blowdown intermediate pressure 180 while
25 releasing "heavy" gas (enriched in the more strongly adsorbed component) to first exhaust means 181. Then, first aperture 34 is opened to second countercurrent blowdown compartment 58, dropping the adsorber pressure to the first countercurrent blowdown intermediate pressure 182 while releasing heavy gas to second exhaust means 183. Finally reaching the lower working pressure, first aperture 34 is opened to heavy product

compartment 60, dropping the adsorber pressure to the lower pressure 152 while releasing heavy gas to third exhaust means 184. Once the adsorber pressure has substantially reached the lower pressure while first aperture 34 is open to compartment 60, the second aperture 35 opens to purge compartment 80, which receives fourth light
5 reflux gas from fourth light reflux pressure let-down means 176 in order to displace more heavy gas into first product compartment 60.

In Fig. 5, the heavy gas from the first, second and third exhaust means is delivered as the heavy product 185. In Fig. 6, this gas is partly released as the heavy product 185,
10 while the balance is redirected as "heavy reflux" 187 to the heavy reflux compressor as fourth feed supply means 167. Just as light reflux enables an approach to high purity of the less readily adsorbed ("light") component in the light product, heavy reflux enables an approach to high purity of the more readily adsorbed ("heavy") component in the heavy product.

15 The adsorber is then repressurized by light reflux gas after the first and second apertures close to compartments 60 and 80. In succession, while the first aperture 34 remains closed at least initially, (a) the second aperture 35 is opened to first light reflux pressurization compartment 82 to raise the adsorber pressure to the first light reflux
20 pressurization pressure 190 while receiving third light reflux gas from the third light reflux pressure letdown means 174, (b) the second aperture 35 is opened to second light reflux pressurization compartment 84 to raise the adsorber pressure to the second light reflux pressurization pressure 191 while receiving second light reflux gas from the second light reflux pressure letdown means 172, and (c) the second aperture 35 is opened to third
25 light reflux pressurization compartment 86 to raise the adsorber pressure to the third light reflux pressurization pressure 192 while receiving first light reflux gas from the first light reflux pressure letdown means 170. Unless feed pressurization has already been started while light reflux return for light reflux pressurization is still underway, the process (as based on Figs. 5 and 6) begins feed pressurization for the next cycle after time 157 as

soon as the third light reflux pressurization step has been concluded.

The pressure variation waveform in each adsorber would be a rectangular staircase if there were no throttling in the first and second valves. In order to provide
5 balanced performance of the adsorbers, preferably all of the apertures are closely identical to each other.

The rate of pressure change in each pressurization or blowdown step will be restricted by throttling in ports (or in clearance or labyrinth sealing gaps) of the first and
10 second valve means, or by throttling in the apertures at first and second ends of the adsorbers, resulting in the typical pressure waveform depicted in Figs. 5 and 6. Alternatively, the apertures may be opened slowly by the seal strips, to provide flow restriction throttling between the apertures and the seal strips, which may have a serrated edge (e.g. with notches or tapered slits in the edge of the seal strip) so that the apertures
15 are only opened to full flow gradually. Excessively rapid rates of pressure change would subject the adsorber to mechanical stress, while also causing flow transients which would tend to increase axial dispersion of the concentration wavefront in the adsorber. Pulsations of flow and pressure are minimized by having a plurality of adsorbers simultaneously transiting each step of the cycle, and by providing enough volume in the
20 function compartments and associated manifolds so that they act effectively as surge absorbers between the compression machinery and the first and second valve means.

It will be evident that the cycle could be generalized by having more or fewer intermediate stages in each major step of feed pressurization, countercurrent blowdown
25 exhaust, or light reflux. Furthermore, in air separation or air purification applications, a stage of feed pressurization (typically the first stage) could be performed by equalization with atmosphere as an intermediate pressure of the cycle. Similarly, a stage of countercurrent blowdown could be performed by equalization with atmosphere as an intermediate pressure of the cycle.

Fig. 7

Fig. 7 is a simplified schematic of a PSA system for separating oxygen from air using nitrogen-selective zeolite adsorbents. The light product is concentrated oxygen, while the heavy product is nitrogen-enriched air usually vented as waste. The cycle lower pressure 152 is nominally atmospheric pressure. Feed air is introduced through filter intake 200 to a feed compressor 201. The feed compressor includes compressor first stage 202, intercooler 203, compressor second stage 204, second intercooler 205, compressor third stage 206, third intercooler 207, and compressor fourth stage 208. The feed compressor 201 as described may be a four stage axial compressor or centrifugal compressor with motor 209 as prime mover coupled by shaft 210, and the intercoolers are optional. The feed compressor first and second stages deliver feed gas at the first intermediate feed pressure 161 via conduit 212 and water condensate separator 213 to first feed pressurization manifold 48. Feed compressor third stage 206 delivers feed gas at the second intermediate feed pressure 163 via conduit 214 and water condensate separator 215 to second feed pressurization manifold 51. Feed compressor fourth stage 208 delivers feed gas at the higher pressure 151 via conduit 216 and water condensate separator 217 to feed manifold 53. Light product oxygen flow is delivered from light product manifold 71 by conduit 218, maintained at substantially the higher pressure less frictional pressure drops.

20

The PSA system of Fig. 7 includes energy recovery expanders, including light reflux expander 220 (here including four stages) and countercurrent blowdown expander 221 (here including two stages), coupled to feed compressor 201 by shaft 222. The expander stages may be provided for example as radial inflow turbine stages, as full admission axial turbine stages with separate wheels, or as partial admission impulse turbine stages combined in a single wheel.

25

Light reflux gas from first light reflux exit manifold 73 flows at the higher pressure via conduit 224 and heater 225 to first light pressure letdown means 170 which

here is first light reflux expander stage 226, and then flows at the third light reflux pressurization pressure 192 by conduit 227 to the first light reflux return manifold 87. Light reflux gas from second light reflux exit manifold 75 flows at the first cocurrent blowdown pressure 171 via conduit 228 and heater 225 to second light reflux pressure
5 letdown means 172, here the second expander stage 230, and then flows at the second light reflux pressurization pressure 191 by conduit 231 to the second light reflux return manifold 85. Light reflux gas from third light reflux exit manifold 77 flows at the second cocurrent blowdown pressure 173 via conduit 232 and heater 225 to third light reflux pressure letdown means 174, here the third expander stage 234, and then flows at the first
10 light reflux pressurization pressure 190 by conduit 235 to the third light reflux return manifold 83. Finally, light reflux gas from fourth light reflux exit manifold 79 flows at the third cocurrent blowdown pressure 175 via conduit 236 and heater 225 to fourth light reflux pressure letdown means 176, here the fourth light reflux expander stage 238, and then flows at substantially the lower pressure 152 by conduit 239 to the fourth light reflux
15 return manifold 81.

Heavy countercurrent blowdown gas from first countercurrent blowdown manifold 57 flows at first countercurrent blowdown intermediate pressure 180 by conduit 240 to heater 241 and thence to first stage 242 of the countercurrent blowdown expander
20 221 as first exhaust means 181, and is discharged from the expander to exhaust manifold 243 at substantially the lower pressure 152. Countercurrent blowdown gas from second countercurrent blowdown manifold 59 flows at second countercurrent blowdown intermediate pressure 182 by conduit 244 to heater 241 and thence to second stage 245 of the countercurrent blowdown expander 221 as second exhaust means 183, and is
25 discharged from the expander to exhaust manifold 243 at substantially the lower pressure 152. Finally, heavy gas from heavy product exhaust manifold 61 flows by conduit 246 as third exhaust means 184 to exhaust manifold 243 delivering the heavy product gas 185 to be vented at substantially the lower pressure 152.

Heaters 225 and 241 raise the temperatures of gases entering expanders 220 and 221, thus augmenting the recovery of expansion energy and increasing the power transmitted by shaft 222 from expanders 220 and 221 to feed compressor 201, and reducing the power required from prime mover 209. While heaters 225 and 241 are means to provide heat to the expanders, intercoolers 203, 205 and 207 are means to remove heat from the feed compressor and serve to reduce the required power of the higher compressor stages. The intercoolers 203, 205, 207 are optional features of the invention.

If light reflux heater 249 operates at a sufficiently high temperature so that the exit temperature of the light reflux expansion stages is higher than the temperature at which feed gas is delivered to the feed manifolds by conduits 212, 214 and 216, the temperature of the second ends 35 of the adsorbers 24 may be higher than the temperature of their first ends 34. Hence, the adsorbers have a thermal gradient along the flow path, with higher temperature at their second end relative to the first end. This is an extension of the principle of "thermally coupled pressure swing adsorption" (TCPSA), introduced by Keefer in U.S. Patent No. 4,702,903. Adsorber rotor 11 then acts as a thermal rotary regenerator, as in regenerative gas turbine engines having a compressor 201 and an expander 220. Heat provided to the PSA process by heater 225 assists powering the process according to a regenerative thermodynamic power cycle, similar to advanced regenerative gas turbine engines approximately realizing the Ericsson thermodynamic cycle with intercooling on the compression side and interstage heating on the expansion side. In the instance of PSA applied to oxygen separation from air, the total light reflux flow is much less than the feed flow because of the strong bulk adsorption of nitrogen. Accordingly the power recoverable from the expanders is much less than the power required by the compressor, but will still contribute significantly to enhanced efficiency of oxygen production.

If high energy efficiency is not of highest importance, the light reflux expander

stages and the countercurrent blowdown expander stages may be replaced by restrictor orifices or throttle valves for pressure letdown. The schematic of Fig. 7 shows a single shaft supporting the compressor stages, the countercurrent blowdown or exhaust expander stages, and the light reflux stages, as well as coupling the compressor to the prime mover. However, it should be understood that separate shafts and even separate prime movers may be used for the distinct compression and expansion stages within the scope of the present invention.

Fig. 8

Fig. 8 shows a PSA system with heavy product reflux for hydrogen recovery from petroleum refinery offgases, e.g. hydrotreater purge gases typically containing light hydrocarbon gases with 30% to 70% hydrogen. Using typical adsorbents, e.g. activated carbon or zeolites, the hydrocarbon impurities will be much more readily adsorbed than hydrogen, so the purified hydrogen will be the light product delivered at the higher working pressure which may be only slightly less than the feed supply pressure, while the impurities will be concentrated as the heavy product and will be exhausted from the PSA process as "PSA tail gas" at the lower working pressure. The tail gas is often either flared or used as fuel gas.

The PSA system of Fig. 8 has infeed conduit 300 to introduce the feed gas at substantially the higher pressure to first feed manifold 53. All but the final pressurization steps are achieved with light reflux gas, with the final feed pressurization step being achieved through manifold 55.

The PSA system includes a multistage heavy reflux compressor 301 driven by prime mover 209 through shaft 210, and by light reflux expander 220 through shaft 309. The heavy reflux compressor 301 includes a first stage 302 drawing heavy gas by conduit 246 from first product exhaust manifold 61, and compressing this gas through intercooler 303 to second stage 304. Heavy reflux compressor second stage 304 draws heavy gas

from second countercurrent blowdown manifold 59 through conduit 244, and delivers this gas by intercooler 305 to third stage 306 which also draws heavy gas from first countercurrent blowdown manifold 57 through conduit 240, and delivers this gas by intercooler 307 to fourth stage 308 which attains substantially the higher working pressure of the PSA cycle.

The compressed heavy gas is conveyed from compressor fourth stage 308 by conduit 310 to condensate separator 311, from which the heavy product is delivered by conduit 312 which is externally maintained at substantially the higher pressure less frictional pressure drops. Condensed vapours (such as water or liquid hydrocarbons) are removed through conduit 313 at substantially the same pressure as the heavy product in conduit 312. The remaining heavy gas flow, after removal of the first product gas, flows by conduit 314 to the second feed manifold 55 as heavy reflux to the adsorbers following the feed step for each adsorber. The heavy reflux gas is a second feed gas, of higher concentration in the more readily adsorbed component or fraction than the first feed gas.

Figs. 9 and 10

Turning now to Figs. 9 and 10, fuel cell-based electrical current generating systems, according to a first embodiment of the present invention, are shown using a rotary PSA system similar to that shown in Fig. 7 as the basic building block. However, it should be understood that the invention is not limited to electrical current generating systems having rotary PSA modules. Rather other arrangements may be employed without departing from the scope of the invention.

In Fig. 9, the PSA system separates oxygen from air, using nitrogen-selective zeolite adsorbents, as previously described. The light product is concentrated oxygen, while the heavy product is nitrogen-enriched air usually vented as waste. The cycle lower pressure 152 is nominally atmospheric pressure. Feed air is introduced through filter intake 200 to a feed compressor 201. The feed compressor includes compressor first

stage 202, compressor second stage 204, compressor third stage 206, , and compressor fourth stage 208. The feed compressor 201 as described may be a four stage axial compressor or centrifugal compressor with motor 209 as prime mover coupled by shaft 210. Intercoolers between compressor stages are optional. The feed compressor first and
5 second stages deliver feed gas at the first intermediate feed pressure 161 via conduit 212 and water condensate separator 213 to first feed pressurization manifold 48. Feed compressor third stage 206 delivers feed gas at the second intermediate feed pressure 163 via conduit 214 and water condensate separator 215 to second feed pressurization manifold 51. Feed compressor fourth stage 208 delivers feed gas at the higher pressure
10 151 via conduit 216 and water condensate separator 217 to feed manifold 53. Light product oxygen flow is delivered from light product manifold 71 by conduit 218, maintained at substantially the higher pressure less frictional pressure drops.

The apparatus of Fig. 9 includes energy recovery expanders, including light reflux
15 expander 220 (here including four stages) and countercurrent blowdown expander 221 (here including two stages). Expander 221 is coupled to feed compressor 201 by shaft 222. The expander stages may be provided for example as radial inflow turbine stages, as full admission axial turbine stages with separate wheels, or as partial admission turbine stages combined in a single wheel. If high energy efficiency were not of highest
20 importance, the light reflux expander stages and/or the countercurrent blowdown expander stages could be replaced by restrictor orifices or throttle valves for pressure letdown.

Light reflux gas from first light reflux exit manifold 73 flows at the higher
25 pressure via conduit 224 and heater 225 to first light reflux expander stage 226, and then flows at the third light reflux pressurization pressure 192 by conduit 227 to the first light reflux return manifold 87. Light reflux gas from second light reflux exit manifold 75 flows at the first cocurrent blowdown pressure 171 via conduit 228 and heater 225 to the second expander stage 230, and then flows at the second light reflux pressurization

pressure 191 by conduit 231 to the second light reflux return manifold 85. Light reflux gas from third light reflux exit manifold 77 flows at the second cocurrent blowdown pressure 173 via conduit 232 and heater 225 to the third expander stage 234, and then flows at the first light reflux pressurization pressure 190 by conduit 235 to the third light
5 reflux return manifold 83. Finally, light reflux gas from fourth light reflux exit manifold 79 flows at the third cocurrent blowdown pressure 175 via conduit 236 and heater 225 to the fourth light reflux expander stage 238, and then flows at substantially the lower pressure 152 by conduit 239 to the fourth light reflux return manifold 81.

10 Heavy countercurrent blowdown gas from first countercurrent blowdown manifold 57 flows at first countercurrent blowdown intermediate pressure 180 by conduit 240 to heater 241 and thence to first stage 242 of the countercurrent blowdown expander 221, and is discharged from the expander to exhaust manifold 243 at substantially the lower pressure 152. Countercurrent blowdown gas from second countercurrent
15 blowdown manifold 59 flows at second countercurrent blowdown intermediate pressure 182 by conduit 244 to heater 241 and thence to second stage 245 of the countercurrent blowdown expander 221, and is discharged from the expander to exhaust manifold 243 at substantially the lower pressure 152. Finally, heavy gas from heavy product exhaust manifold 61 flows by conduit 246 to exhaust manifold 243 delivering the heavy product
20 gas 185 to be vented at substantially the lower pressure 152.

Optional heaters 225 and 241 raise the temperatures of gases entering expanders 220 and 221, thus augmenting the recovery of expansion energy and increasing the power transmitted by shaft 222 from expanders 220 and 221 to feed compressor 201, and
25 reducing the power required from prime mover 209.

In the instance of PSA applied to oxygen separation from air, the total light reflux flow is much less than the feed flow because of the strong bulk adsorption of nitrogen. Accordingly the power recoverable from the expanders is much less than the power

required by the compressor, but will still contribute significantly to enhanced efficiency of oxygen production. By operating the adsorbers at moderately elevated temperature (e.g. 40° to 60° C) and using strongly nitrogen-selective adsorbents such as Ca-X, Li-X or lithium chabazite zeolites, the PSA oxygen generation system can operate with
5 favourable performance and exceptional efficiency. Calcium or strontium exchanged chabazite may be used at higher temperatures, even in excess of 100° C, reflecting the extraordinary capacity of these adsorbents for nitrogen, their nitrogen uptake being too close to saturation at lower temperatures near ambient for satisfactory operation.

10 While higher temperature of the adsorbent will reduce nitrogen uptake and selectivity for each zeolite adsorbent, the isotherms will be more linear and humidity rejection will be easier. Working with adsorbents such as Ca-X and Li-X, recent conventional practice has been to operate ambient temperature PSA at subatmospheric lower pressures in so-called "vacuum swing adsorption" (VSA), so that the highly
15 selective adsorbents operate well below saturation in nitrogen uptake, and have a large working capacity in a relatively linear isotherm range. At higher temperatures, saturation in nitrogen uptake is shifted to more elevated pressures, so the optimum PSA cycle higher and lower pressures are also shifted upward. For satisfactory operation of the apparatus of Fig. 10, the typical operating temperature of the second ends of the adsorbers may be
20 approximately 50°C for Ca-X, 80°C for Li-X and 100° to 150°C for calcium chabazite.

The enriched oxygen product gas is delivered by conduit 218, non-return valve 250, and conduit 251 to the inlet of oxygen product compressor 252 which boosts the pressure of product oxygen delivered by conduit 253. Compressor 252 may be a single
25 stage centrifugal compressor, driven directly through shaft 254 by light reflux expander 220 or alternatively by a motor. Light reflux expander 220 may be the sole power source to compressor 252, in which case expander 220 and compressor 252 together constitute a free rotor turbo-booster 255. Since the working fluid in both expander 220 and compressor 252 is enriched oxygen, the free rotor turbo-booster embodiment has the

important safety feature of not requiring a shaft seal to an external motor. Energy recovered from light reflux expansion is most usefully applied to raising the delivery pressure of product oxygen.

5 The compressed enriched oxygen is delivered to a fuel cell 260, by conduit 253 to cathode inlet 261 of fuel cell cathode channel 262. Fuel cell 260 may be of the polymer electrolyte membrane (PEM) type, with the membrane 265 separating cathode channel 262 from anode channel 266. Hydrogen fuel is supplied to anode inlet 267 of anode channel 266 by hydrogen infeed conduit 268.

10

 The enriched oxygen passes through cathode channel 262 to cathode exit 270, as a fraction of the oxygen reacts with hydrogen ions crossing the membrane to generate electrical power and reacting to form byproduct water. The cathode exit gas leaving the cathode channel in conduit 280 from cathode exit 270 (in this preferred embodiment) is
15 still significantly enriched in oxygen relative to ambient air concentration of approximately 21%. A minor portion of this gas is purged as cathode purge gas from conduit 280 by purge valve 285 and purge exhaust 286, and the balance of the cathode exit gas is retained as cathode recycle gas. The cathode recycle gas is conveyed by conduit 281 to water condensate separator 282 where excess liquid water is removed from
20 the cathode exit gas, which remains saturated in water vapour. The humid cathode recycle gas is then blended with incoming enriched oxygen from the PSA system by conduit 283 connecting to conduit 251.

 Conduits 251, 253, 280, 281 and 283 thus form a cathode loop with cathode
25 channel 262, compressor 252 and water condensate separator 282. Heat exchanger 225 may cool the oxygen enriched gas to be compressed by compressor 252, by removing waste heat from the fuel cell cathode loop to heat light reflux gas before expansion in expander 220. Enough of the cathode exit gas is purged by purge valve 285 to avoid excessive build-up of argon and nitrogen impurities in the cathode loop. In a practicable

example, the product oxygen concentration in conduit 218 may be 90% oxygen, with equal amounts of argon and nitrogen impurities. With a small purge flow, oxygen concentrations at cathode inlet 261 and at cathode exit 270 may be respectively 60% and 50%.

5

As discussed above, a PEM fuel cell operating with atmospheric air as oxidant may typically require air compression to at least 3 atmospheres in order to achieve a sufficiently high oxygen partial pressure over the cathode for competitive current density in the fuel cell stack. Oxygen concentration at the cathode inlet would be 21%, and at the cathode exit typically only about 10% oxygen. The present invention can achieve much higher average oxygen concentration over the fuel cell cathode channel, e.g. 55% compared to approximately 15%. Hence, the operating pressure may be reduced to about 1.5 atmospheres while still retaining a substantial enhancement of oxygen partial pressure over the cathode. With higher oxygen partial pressure over the cathode, fuel cell stack power density and efficiency can be enhanced, as is particularly crucial in automotive power plant applications. Mechanical compression power required by the apparatus of the present invention (using high performance adsorbents such as Li-X) will be less than that required for the air compressor of a PEM fuel cell system operating at 3 atmospheres air supply pressure, further enhancing overall power plant efficiency.

20

An important benefit in this example apparatus is that the oxygen enriched gas entering cathode inlet 261 is humidified by blending with the much larger stream of saturated cathode recycle gas. Another benefit is that energy recovery from the PSA unit can be applied to boost pressure and drive recycle circulation in the cathode loop, while fuel cell waste heat can be applied to heat exchangers 225 and 241 to enhance expansion energy recovery in the PSA unit.

25

Turning to Fig. 10, an oxygen-separating PSA-based fuel cell system is shown, similar to the fuel cell system of Fig. 9, but with a countercurrent blowdown expander

driving a free rotor exhaust vacuum pump. In the embodiment of Fig. 10, shaft 222 coupling the countercurrent blowdown expander 221 to feed compressor 201 has been removed. Instead, vacuum pump 301 is used to depress the low pressure of the cycle below atmospheric pressure, drawing nitrogen-enriched waste gas from heavy product exhaust compartment 61 via conduit 246 and optional heater 302. Pump 301 is powered by countercurrent blowdown expander 304 expanding countercurrent blowdown gas from first countercurrent blowdown manifold 57 via conduit 240 and optional heater 241. Vacuum pump 301 and expander 304 are coupled by shaft 305, and together constitute free rotor vacuum pump assembly 306. Alternatively, a motor could be coupled to an extension of shaft 305.

The countercurrent blowdown gas from second countercurrent blowdown manifold 59 exits that manifold at a pressure which is substantially atmospheric or slightly greater according to the amount of throttling restriction associated with conduit 244.

Fig. 11

Fig. 11 shows fuel cell-based electrical current generating system, similar to the electrical current generating system of Fig. 9, but without light reflux energy recovery, and with a portion of oxygen enriched gas discharged from the fuel cell cathode being used for a pressurization step. The illustrative four stages of light reflux pressure letdown are achieved irreversibly over adjustable orifices 350, 351, 352 and 353 which respectively connect conduits 224 and 227, 228 and 231, 232 and 235, and 236 and 239. Orifices 350, 351, 352 and 353 are actuated through linkage 354 by actuator(s) 355. Adjustment of the orifices is desirable to enable turndown of the PSA apparatus to operation at reduced cycle frequency and reduced flow rates when the fuel cell power plant is operated at part load.

The fuel cell has a cathode recycle loop defined (in the loop flow direction) by

water condensate separator 360, conduit 361 conveying enriched oxygen to cathode channel inlet 261, cathode channel 262, conduit 362 conveying cathode exhaust gas from cathode channel exit 270 to cathode recycle conduit 365 including cathode recycle blower 363 to repressurize the cathode recycle gas for admission to condensate separator 360.

- 5 Separator 360 removes fuel cell water exhaust condensate from the cathode recycle loop, while also humidifying the dry concentrated oxygen admitted from the PSA system conduit from conduit 218.

- 10 A portion of the cathode exhaust is removed from conduit 362 by conduit 371, branching from cathode recycle conduit 365. This portion of the cathode exhaust gas is recycled to the feed end of the PSA apparatus, and is conveyed by conduit 371 to water condensate separator 373 and thence to first pressurization manifold 48 communicating to the first valve face 21. A throttle valve 375 may be provided in conduit 371 to provide a pressure letdown as required from the pressure at cathode exit 270 to first pressurization manifold 48.
- 15

- Recycling a portion of the cathode exhaust gas to the PSA unit feed has several advantages, including (1) reducing the volume of feed gas to be compressed, (2) eliminating the requirement to purge any cathode exhaust gas from the cathode loop, and
- 20 (3) recovering some waste energy from the fuel cell cathode loop by using this gas to help pressurize the fuel cell from the feed end. This oxygen rich gas must be admitted to the feed end of the PSA unit, because it is saturated with water vapour which would deactivate the adsorbent if admitted directly to the second valve face at the product end. By introducing it to the feed end of the beds after the low pressure step and before any
- 25 direct pressurization with feed air, a favourable concentration profile is established since this gas is richer in oxygen than feed air, but also contains a greater load of impurities than the product oxygen-enriched gas.

Because argon is concentrated with oxygen by the PSA unit, argon will be

concentrated both within the cathode loop and in the PSA enriched oxygen product in this embodiment. If no cathode purge is provided, argon can only exit the system through the exhaust of the PSA unit. Since the PSA unit typically achieves about 60% recovery of oxygen and argon when ordinary air is used as the only feed for pressurization to the first valve face, about 40% of argon admitted with feed gas may be exhausted in each cycle. The fractional elimination of recycle argon introduced with initial feed pressurization steps will be lower, since the main feed is introduced subsequently to push the recycle argon deeper into the adsorbers. Hence, a small amount of purge from the cathode loop may be desirable. Cathode exhaust gas recycle to the PSA unit feed may also be blended directly with feed air introduced at the same or lower pressure as the cathode channel exit

270.

Fig. 12

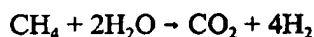
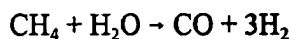
Fig. 12 shows a fuel-cell based electrical current generating system 400, according to a second embodiment of the present invention, comprising a fuel cell 402, an oxygen-generating PSA system 404, and a hydrogen gas production system 406. The fuel cell comprises an anode channel 408 including an anode gas inlet 410 and an anode gas outlet 412, a cathode channel 414 including a cathode gas inlet 416 and a cathode gas outlet 418, and a PEM 420 in communication with the anode channel 408 and the cathode channel 414 for facilitating ion exchange between the anode channel 408 and the cathode channel 414.

The oxygen-PSA system 404 extracts oxygen gas from feed air, and comprises a rotary module 10, and a compressor 422 for delivering pressurized feed air to the feed compartments 424 of the rotary module 10. Preferably, the oxygen-PSA system 404 includes a vacuum pump 426 coupled to the compressor 422 for withdrawing nitrogen-enriched gas as heavy product gas from the blowdown compartments 428 of the rotary module 10. The oxygen-PSA system 404 also includes a light product gas function compartment 430 coupled to the cathode gas inlet 416 for delivering oxygen-enriched gas

to the cathode channel 414.

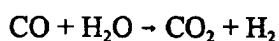
The hydrogen gas production system 406 comprises a hydrogen-generating PSA system 432, and a reactor 434 coupled to the hydrogen-PSA system 432 for supplying a first hydrogen gas feed to the hydrogen-PSA system 432. The hydrogen-PSA system 432 comprises a rotary module 10 including a first feed compartment 436 for receiving the first hydrogen gas feed from the reactor 434, a second feed compartment 438 for receiving a second hydrogen gas feed from the anode gas outlet 412, a light product compartment 440 for delivering hydrogen gas to the anode gas inlet 410, and a blowdown compartment 442 for delivering tail gas as heavy product gas to the reactor 434. Preferably the hydrogen-PSA system 432 includes a vacuum pump 443 provided between the blowdown compartment 442 and the reactor 434 for extracting the tail gas from the blowdown compartment 442. The hydrogen-PSA system 432 may also include a heavy reflux stage to improve the fractional recovery of hydrogen gas, if desired.

The reactor 434 comprises a steam reformer 444, including a burner 446 and catalyst tubes (not shown), and a water gas shift reactor 448. The burner 446 includes a first burner inlet 450 for receiving the tail gas from the blowdown compartment 442, and a second burner inlet 452 for receiving humid oxygen-enriched gas from the cathode channel 414. The steam reformer 444 is supplied through a fuel inlet 454 with a hydrocarbon fuel gas, such as methane gas, which is mixed with steam produced when the tail gas and the humid oxygen-enriched gas are burned in the burner 446. The methane fuel gas mixture is then passed through the catalyst tubes, while the tail gas and the oxygen-enriched gas are burned in the burner 446 to elevate the temperature of the methane fuel gas mixture to the 800°C temperature necessary for conducting endothermic steam reforming reactions of the methane fuel gas mixture:



The resulting syngas (approximately 70% H₂, with equal amounts of CO and CO₂ as major impurities, and unreacted CH₄ and N₂ as minor impurities) is cooled to about 250°C, and then passed to the water gas shift reactor 448 for reacting most of the CO with steam to produce more H₂ and CO₂:

5

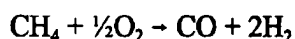


The resulting gas reactants are then conveyed to the first feed compartment 436 of the hydrogen-PSA system 432 for hydrogen purification, with the heavy product tail gas being returned to the steam reformer 434 from the blowdown compartment 442 for combustion in the burner 446.

10

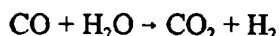
In one variation, the reactor 434 comprises a partial oxidation reactor, and instead of the methane gas mixture being steam reformed, the methane gas mixture is reacted in the partial oxidation reactor with a portion of the humid oxygen-enriched gas from the cathode channel 414 for partial oxidation of the methane gas:

15



The resulting syngas is again cooled to about 250°C, and then passed to the water gas shift reactor 448 for reacting most of the CO with steam to produce more H₂ and CO₂:

20



The resulting gas reactants are then conveyed to the first feed compartment 436 of the hydrogen-PSA system 432 for hydrogen purification, with the heavy product tail gas being purged from the hydrogen-PSA system 432.

25

In another variation, the reactor 434 comprises an autothermal reformer and a

water gas shift reactor 448, and instead of the methane gas mixture being steam reformed or partially oxidized, the methane gas mixture is reacted in the autothermal reformer, followed by reaction in the water gas shift reactor 448.

5 Fig. 13

It will be apparent that a principle deficiency of the electrical current generating system 400 relates to the necessity of driving the compressor 422 and the vacuum pumps 426, 444 with a portion of the electrical power generated by the fuel cell. Fig. 13 shows a fuel-cell based electrical current generating system 500, which addresses this deficiency.

10

The electrical current generating system 500 is substantially similar to the electrical current generating system 400, comprising the fuel cell 402, an oxygen-generating PSA system 504, and a hydrogen gas production system 506. The oxygen-PSA system 504 extracts oxygen gas from feed air, and comprises a rotary module 10, a
15 compressor 522 for delivering pressurized feed air to the feed compartments 524 of the rotary module 10, an expander 523 coupled to the compressor 522, and a light product gas function compartment 530 coupled to the cathode gas inlet 416 for delivering oxygen-enriched gas to the cathode channel 414.

20 The hydrogen gas production system 506 comprises a hydrogen-generating PSA system 532, and a reactor 534 coupled to the hydrogen-PSA system 532 for supplying a first hydrogen gas feed to the hydrogen-PSA system 532. The hydrogen-PSA system 532 comprises a rotary module 10 including a first feed compartment 536 for receiving the first hydrogen gas feed from the reactor 534, a second feed compartment 538 for
25 receiving a second hydrogen gas feed from the anode gas outlet 412, a light product compartment 540 for delivering hydrogen gas to the anode gas inlet 410, and a blowdown compartment 542 for delivering tail gas as heavy product gas to the reactor 534.

The reactor 534 comprises an autothermal reformer 544, a burner 546, and a water

gas shift reactor 548. The burner 546 includes a first burner inlet 550 for receiving the tail gas from the blowdown compartment 542, and a second burner inlet 552 for receiving oxygen-enriched gas from the compressor 522. Burned exhaust gas emanating from the burner 546 is expanded through the expander 523, and is used to increase the pressure of feed air to the feed compartments 524. As shown in Fig. 13, additional feed gas compression energy may be obtained from the exothermic heat of reaction of the water gas shift reactor 548.

The autothermal reformer 544 is supplied through a fuel inlet 554 with a hydrocarbon fuel gas, such as methane gas, and is reacted with oxygen-enriched gas received under pressure from the cathode channel 414 through blower 556. The resultant syngas is then cooled, and then passed to the water gas shift reactor 548 for reacting most of the CO with steam to produce more H₂ and CO₂. The resulting gas reactants are then conveyed to the first feed compartment 536 of the hydrogen-PSA system 532 for hydrogen purification.

The foregoing description is intended to be illustrative of the preferred embodiments of the present invention. Those of ordinary skill may envisage certain additions, deletions and/or modifications to the described embodiments which, although not specifically described or referred to herein, do not depart from the spirit or scope of the present invention as defined by the appended claims.

WE CLAIM:

1. An electrical current generating system comprising:
a fuel cell including an anode channel including an anode gas inlet for receiving a supply of hydrogen gas, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;
an oxygen gas delivery system coupled to the cathode gas inlet for delivering oxygen gas to the cathode channel; and
first gas recirculation means coupled to the cathode gas outlet for recirculating a first portion of cathode exhaust gas exhausted from the cathode channel to the cathode gas inlet.
2. The current generating system according to claim 1, wherein the first gas recirculating means comprises a compressor for supplying the first cathode exhaust gas portion under pressure to the cathode gas inlet.
3. The current generating system according to claim 2, wherein the first gas recirculation means includes a condensate separator coupled between the cathode gas outlet and the compressor for removing moisture from the first cathode exhaust gas portion.
4. The current generating system according to claim 1, wherein the oxygen gas delivery system comprises a gas separation system for extracting oxygen gas from air, the gas separation system including a first feed gas inlet for receiving an air feed, and an oxygen gas outlet coupled to the cathode gas inlet for supplying oxygen gas extracted from the air feed to the cathode channel.
5. The current generating system according to claim 4, wherein the gas recirculating means directs the first cathode exhaust gas portion as feed gas to the gas separation system.

6. The current generating system according to claim 4, wherein the gas separation system includes a second feed gas inlet, and the current generating system includes second gas recirculating means coupled to the cathode gas outlet for recirculating a second portion of the cathode exhaust gas to the second feed gas inlet.
7. The current generating system according to claim 6, wherein the recirculating means comprises a restrictive orifice for delivering the second cathode exhaust gas portion to the gas separation system at a pressure less than a pressure of the air feed.
8. The current generating system according to claim 4, wherein the gas separation system comprises a pressure swing adsorption system.
9. The current generating system according to claim 8, wherein the pressure swing adsorption system comprises a rotary module including a stator and a rotor rotatable relative to the stator, the rotor including a plurality of flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component, and compression machinery coupled to the rotary module for facilitating gas flow through the flow paths for separating the first gas component from the second gas component.
10. The current generating system according to claim 9, wherein the stator includes a first stator valve surface, a second stator valve surface, a plurality of first function compartments opening into the first stator valve surface, and a plurality of second function compartments opening into the second stator valve surface, and the rotor includes a first rotor valve surface in communication with the first stator valve surface, a second rotor valve surface in communication with the second stator valve surface, and a plurality of apertures provided in the rotor valve surfaces and in communication with respective ends of the flow paths and the function compartments.

11. The current generating system according to claim 10, wherein the compression machinery is coupled to a portion of the function compartments for maintaining the portion of function compartments at a plurality of discrete respective pressure levels between an upper pressure and a lower pressure for maintaining uniform gas flow through the portion of function compartments.

12. The current generating system according to claim 10, wherein the function compartments include a light reflux exit compartment and a light reflux return compartment, the compression machinery comprises a light reflux expander coupled between the light reflux exit and return compartments, and the first gas recirculation means comprises a compressor coupled to the light reflux expander for supplying the first cathode exhaust gas portion under pressure to the cathode gas inlet.

13. The current generating system according to claim 12, wherein the pressure swing adsorption system includes a heater disposed between the light reflux exit compartment and the light reflux expander for enhancing recovery of energy from light reflux gas exhausted from the light reflux exit compartment.

14. The current generating system according to claim 12, wherein the function compartments include a gas feed compartment and a countercurrent blowdown compartment, and the compression machinery comprises a compressor coupled to the first feed gas inlet for delivering compressed air to the gas feed compartment, and an expander coupled to the compressor for exhausting heavy product gas enriched in the first gas component from the countercurrent blowdown compartment.

15. The current generating system according to claim 12, wherein the function compartments include countercurrent blowdown compartments, and the compression machinery comprises an expander coupled to one of the countercurrent blowdown compartments, and a vacuum pump coupled to the expander for extracting heavy product gas enriched in the first gas component at

subatmospheric pressure from another of the countercurrent blowdown compartments.

16. The current generating system according to claim 10, wherein the function compartments include a gas feed compartment, and the gas recirculating means directs the first cathode exhaust gas portion as feed gas to the gas feed compartment.

17. The current generating system according to claim 10, wherein the function compartments include a gas feed compartment, and the current generating system includes second gas recirculating means coupled to the cathode gas outlet for recirculating a second portion of the cathode exhaust gas to the gas feed compartment.

18. The current generating system according to claim 17, wherein the second gas recirculating means comprises a restrictor orifice.

19. The current generating system according to claim 9, wherein the adsorbent material is one of Ca-X, Li-X, lithium chabazite zeolite, calcium-exchanged chabazite and strontium-exchanged chabazite.

20. Electrical current generated by the electrical current generating system according to claim 1.

21. An electrical current generating system comprising:

a fuel cell including an anode channel including an anode gas inlet and an anode gas outlet, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;

an oxygen gas delivery system coupled to the cathode gas inlet for delivering oxygen gas to the cathode channel; and

a hydrogen gas delivery system including a hydrogen gas inlet for receiving a first

hydrogen gas feed from the anode gas outlet, and a hydrogen gas outlet coupled to the anode gas inlet for delivering hydrogen gas to the anode channel with increased purity from the first hydrogen gas feed.

22. The electrical current generating system according to claim 21, wherein the oxygen gas delivery system comprises an oxygen gas separation system for extracting oxygen gas from air, the gas separation system including a first feed gas inlet for receiving an air feed, and an oxygen gas outlet coupled to the cathode gas inlet for supplying the extracted oxygen gas to the cathode channel from the air feed.

23. The electrical current generating system according to claim 22, wherein the hydrogen gas delivery system comprises a reactor for producing a second hydrogen gas feed from hydrocarbon fuel, and a hydrogen gas separation system coupled to the reactor for purifying hydrogen gas received from the first and second hydrogen gas feeds.

24. The electrical current generating system according to claim 21, wherein the hydrogen gas delivery system comprises a reactor for producing a second hydrogen gas feed from hydrocarbon fuel, and a hydrogen gas separation system coupled to the reactor for purifying hydrogen gas received from the first and second hydrogen gas feeds.

25. The electrical current generating system according to claim 24, wherein the hydrogen gas separation system receives the first hydrogen gas feed, and a second hydrogen gas feed from the reformer outlet, and produces the purified hydrogen from the first and second hydrogen gas feeds.

26. The electrical current generating system according to claim 25, wherein the hydrogen gas separation system includes a first feed gas inlet for receiving the first hydrogen gas feed, and a second feed gas inlet for receiving the second hydrogen gas feed.

27. The electrical current generating system according to claim 26, wherein the first hydrogen gas feed is provided at a pressure level different from a pressure level of the second hydrogen gas feed.

28. The electrical current generating system according to claim 24, wherein the reactor comprises a steam reformer, and a water gas shift reactor coupled to the steam reformer for producing the second hydrogen gas feed.

29. The electrical current generating system according to claim 28, wherein the steam reformer includes a burner including a first burner inlet coupled to the cathode gas outlet for receiving humid oxygen-enriched gas, and a second burner inlet for receiving hydrogen gas from the hydrogen gas separation system for burning within the burner for providing endothermic heat of reaction for steam reforming of the hydrocarbon fuel.

30. The electrical current generating system according to claim 24, wherein the reactor comprises an autothermal reformer, and a water gas shift reactor coupled to the steam reformer for producing the second hydrogen gas feed.

31. The electrical current generating system according to claim 30, wherein the oxygen gas delivery system comprises an oxygen gas separation system for extracting oxygen gas from air, the gas separation system including a first feed gas inlet for receiving an air feed, and an oxygen gas outlet coupled to the cathode gas inlet for supplying the extracted oxygen gas to the cathode channel from the air feed, and the reactor includes a burner including a first burner inlet for receiving air, and a second burner inlet for receiving hydrogen gas from the hydrogen gas separation system for burning the received hydrogen gas within the burner for recovery of heat energy for pressurizing the air feed.

32. The electrical current generating system according to claim 23, wherein at least one of the oxygen gas separation system and the hydrogen gas separation system comprises a pressure

swing adsorption system.

33. The electrical current generating system according to claim 32, wherein at least one of the pressure swing adsorption systems comprises a rotary module including a stator and a rotor rotatable relative to the stator, the rotor including a plurality of flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component, and compression machinery coupled to the rotary module for facilitating gas flow through the flow paths for separating the first gas component from the second gas component.

34. The current generating system according to claim 33, wherein the stator includes a first stator valve surface, a second stator valve surface, a plurality of first function compartments opening into the first stator valve surface, and a plurality of second function compartments opening into the second stator valve surface, and the rotor includes a first rotor valve surface in communication with the first stator valve surface, a second rotor valve surface in communication with the second stator valve surface, and a plurality of apertures provided in the rotor valve surfaces and in communication with respective ends of the flow paths and the function compartments.

35. The current generating system according to claim 34, wherein the compression machinery is coupled to a portion of the function compartments for maintaining the portion of function compartments at a plurality of discrete respective pressure levels between an upper pressure and a lower pressure for maintaining uniform gas flow through the portion of function compartments.

36. Electrical current generated by the electrical current generating system of claim 21.

37. A method for generating an electric potential comprising the steps of:
providing a fuel cell including an anode channel including an anode gas inlet, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in

communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;

supplying hydrogen gas to the anode gas inlet;

supplying oxygen gas to the cathode gas inlet for reacting with the hydrogen gas;

recirculating a portion of cathode gas exhausted from the cathode gas outlet to the cathode gas inlet.

38. The method according to claim 37, wherein the recirculating step comprises delivering the exhaust gas portion at increased pressure to the cathode gas inlet.

39. The method according to claim 38, wherein the recirculating step further comprises purging a remainder of the exhaust gas.

40. The method according to claim 38, wherein the step of supplying oxygen gas comprises the steps of supplying an air feed to an oxygen pressure swing adsorption apparatus, and delivering oxygen-enriched gas extracted from the air feed as light product gas to the cathode gas inlet, and the recirculating step further comprises recovering waste heat from the fuel cell for enhancing recovery of expansion energy from the pressure swing adsorption apparatus.

41. The method according to claim 38, wherein the step of supplying oxygen gas comprises the steps of supplying an air feed to an oxygen pressure swing adsorption apparatus as a first gas feed, and delivering oxygen-enriched gas extracted from the first gas feed as light product gas to the cathode gas inlet, and the recirculating step further comprises delivering a remainder of the exhaust gas to the pressure swing adsorption apparatus as a second gas feed.

42. A method for generating electrical potential comprising the steps of:
providing a fuel cell including an anode channel including an anode gas inlet, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the

anode and cathode channel;

supplying hydrogen gas to the anode gas inlet;

supplying oxygen gas to the cathode gas inlet; and

recirculating a portion of anode gas exhausted from the anode gas outlet to the anode gas inlet.

43. The method according to claim 42, wherein the step of supplying hydrogen gas comprises the steps of supplying a hydrocarbon fuel to a reformer, reacting the fuel with oxygen-enriched gas from the cathode gas outlet, delivering a hydrogen gas feed from the reformer as a first gas feed to a hydrogen pressure swing adsorption apparatus, and delivering hydrogen-enriched gas extracted from the first gas feed as light product gas to the anode gas inlet.

44. The method according to claim 43, wherein the recirculating step comprises delivering the exhausted anode gas as a second gas feed to the hydrogen pressure swing adsorption apparatus.

45. The method according to claim 43, wherein the reformer comprises a steam reformer including a combustor, and the reacting step comprises delivering the fuel to the combustor, and providing heat energy to the combustor by burning tail gas extracted from the hydrogen pressure swing adsorption apparatus as heavy product gas with the oxygen-enriched gas in the combustor.

46. The method according to claim 43, wherein the step of supplying oxygen gas comprises the steps of supplying a pressurized air feed to an oxygen pressure swing adsorption apparatus, and delivering oxygen-enriched gas extracted from the air feed as light product gas to the cathode gas inlet.

47. The method according to claim 46, wherein the reformer comprises an autothermal reformer including a water gas shift reactor, and the step of supplying a pressurized air feed comprises the steps of delivering air to a combustor, burning tail gas extracted from the hydrogen

pressure swing adsorption apparatus as heavy product gas with the delivered air in the combustor, and recovering heat of combustion from the combustor for delivering air under pressure to the oxygen pressure swing adsorption apparatus.

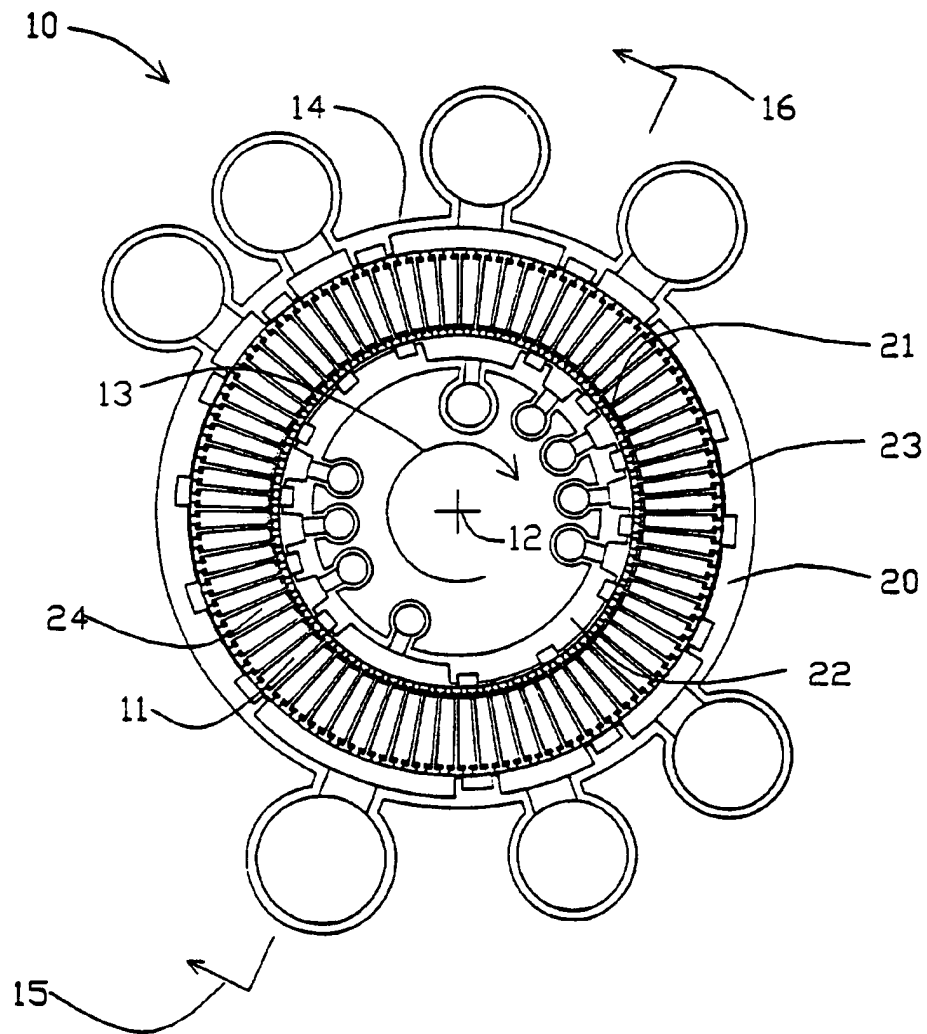


Fig. 1

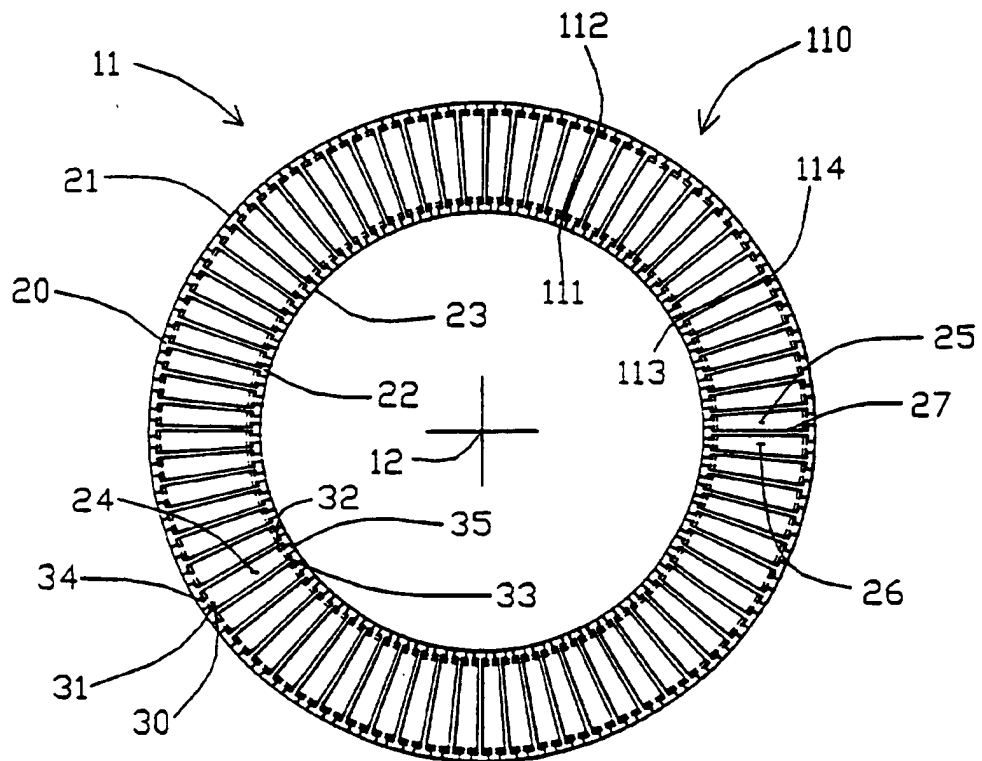


Fig. 2

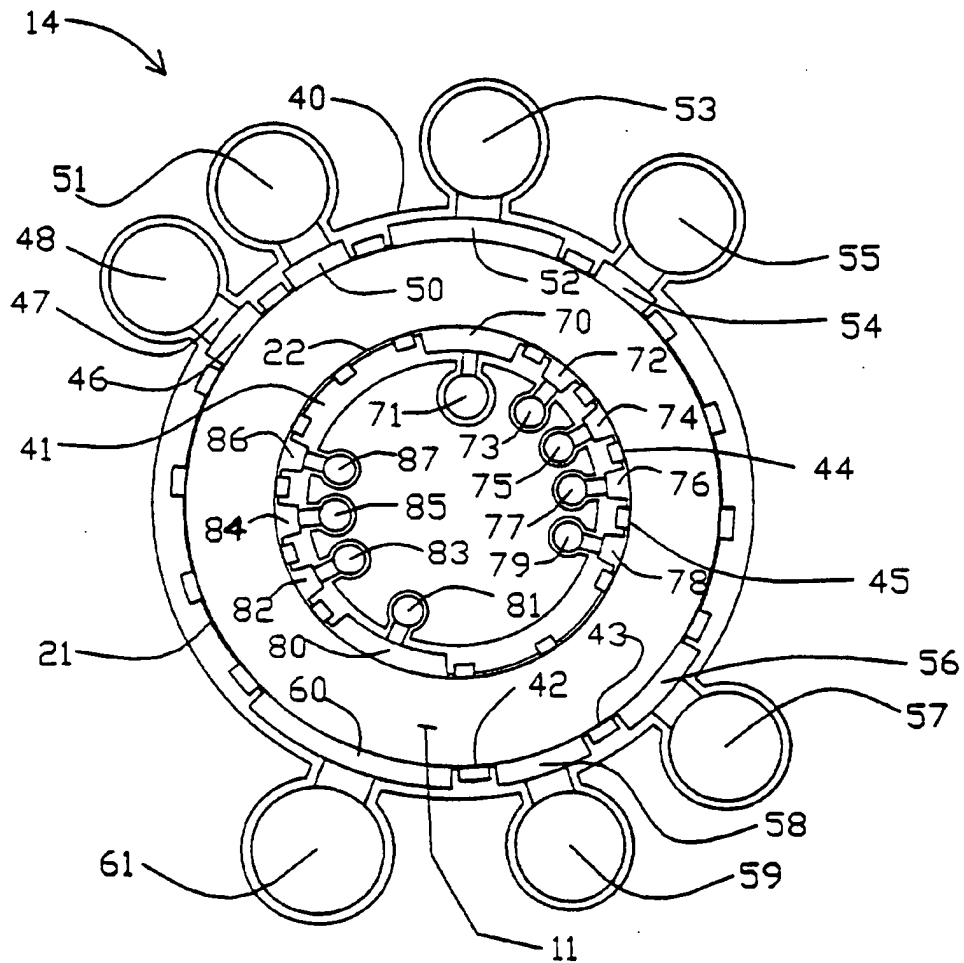


Fig. 3

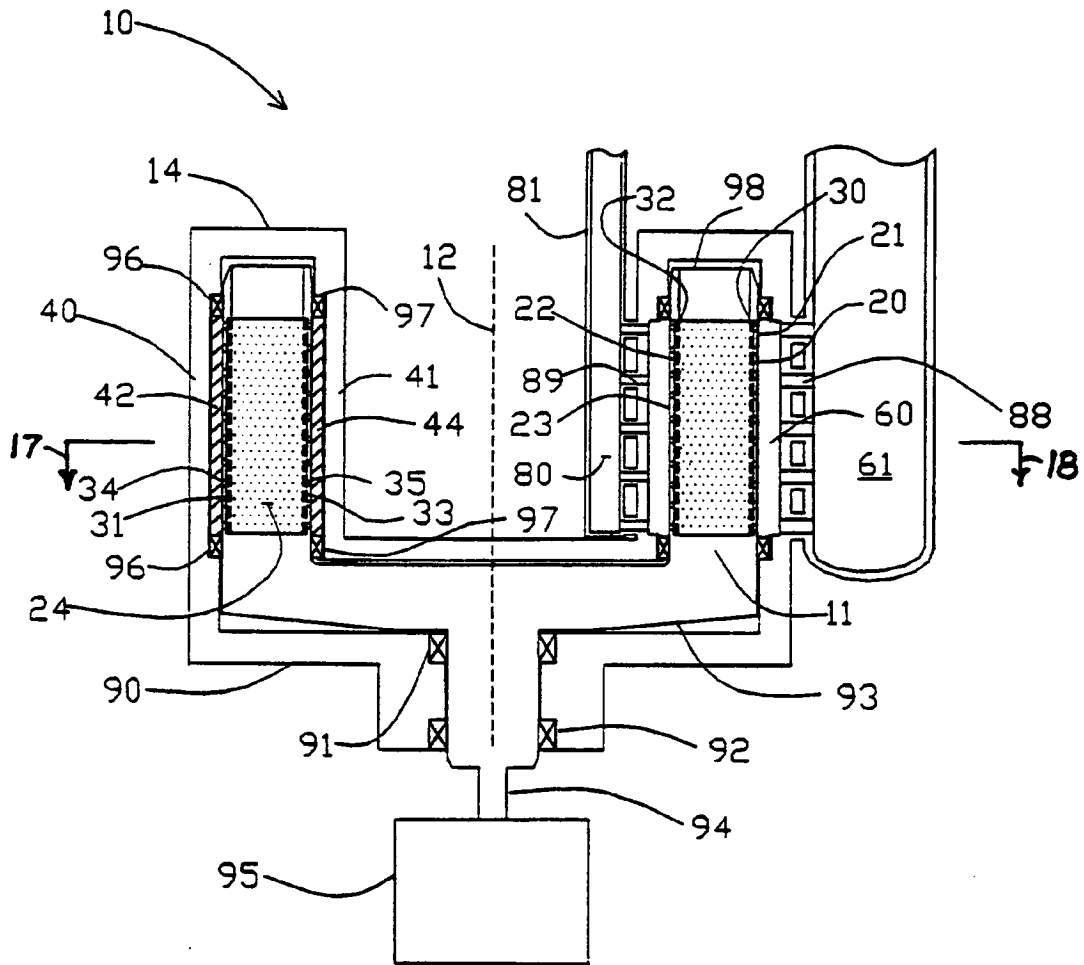


Fig. 4

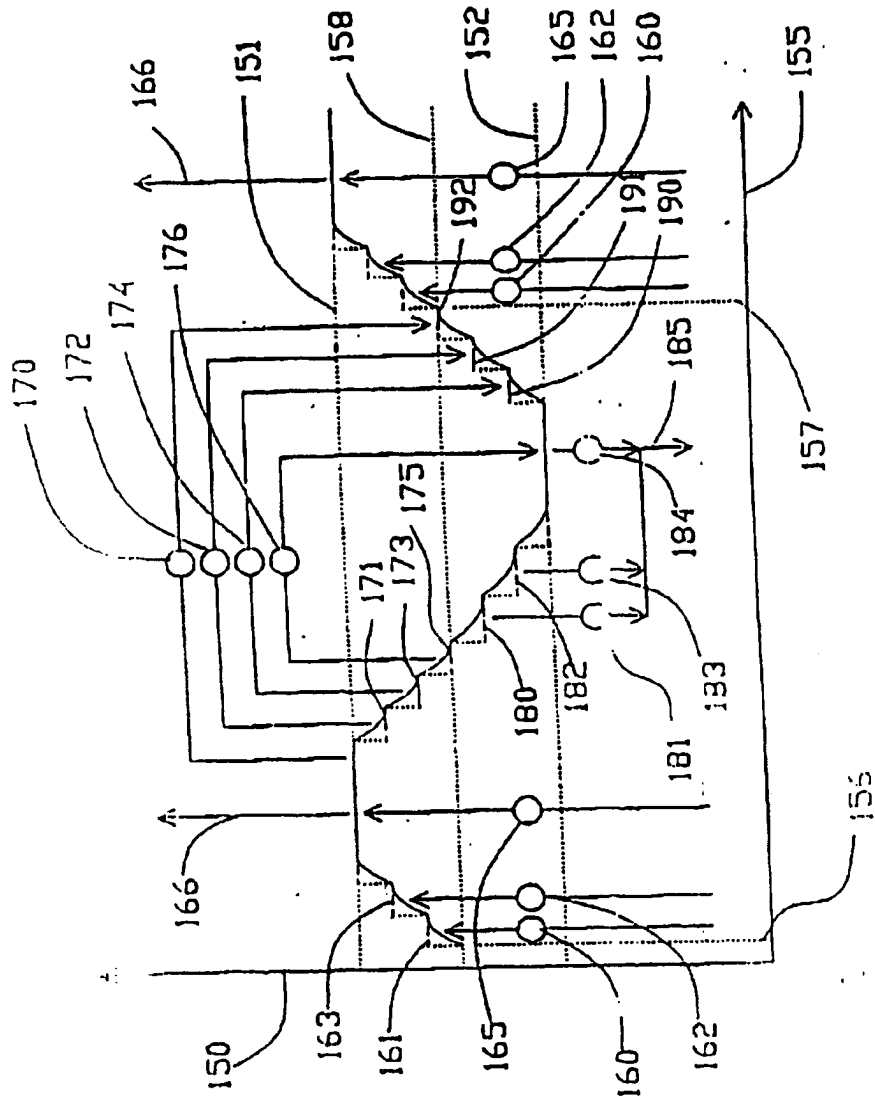


FIG. 5

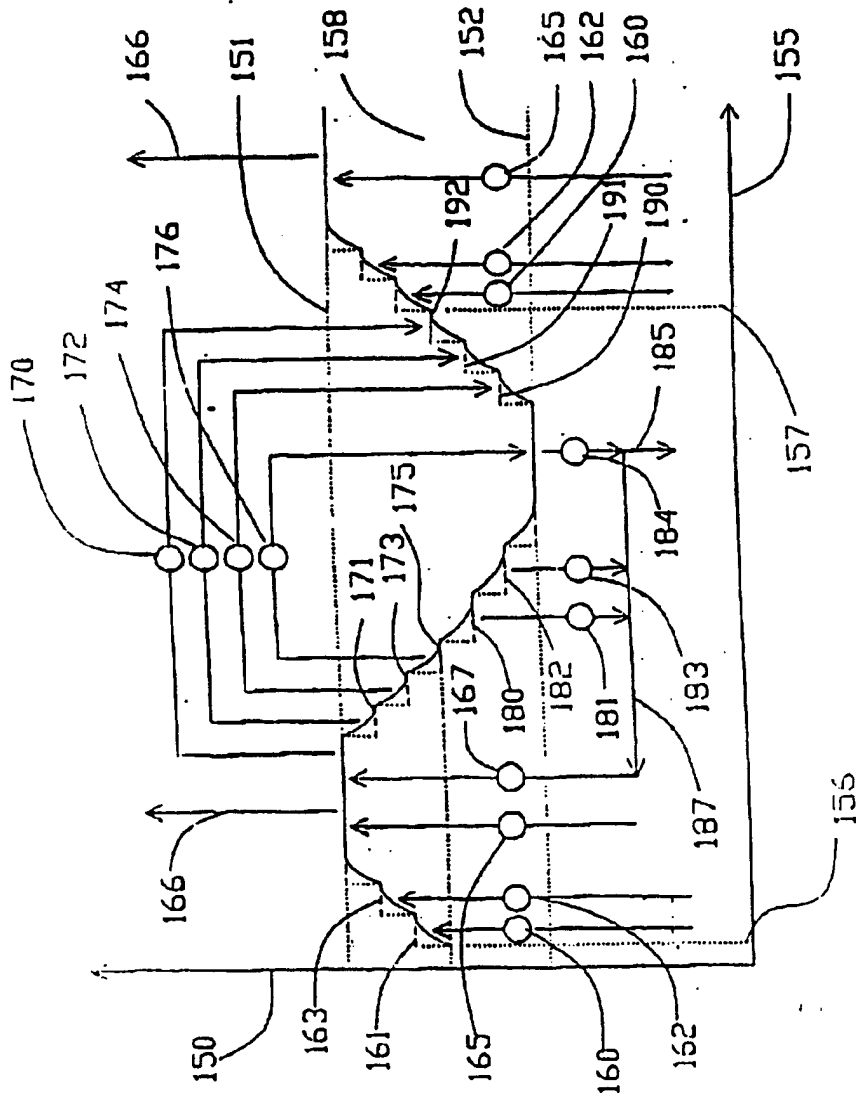


Fig. 6

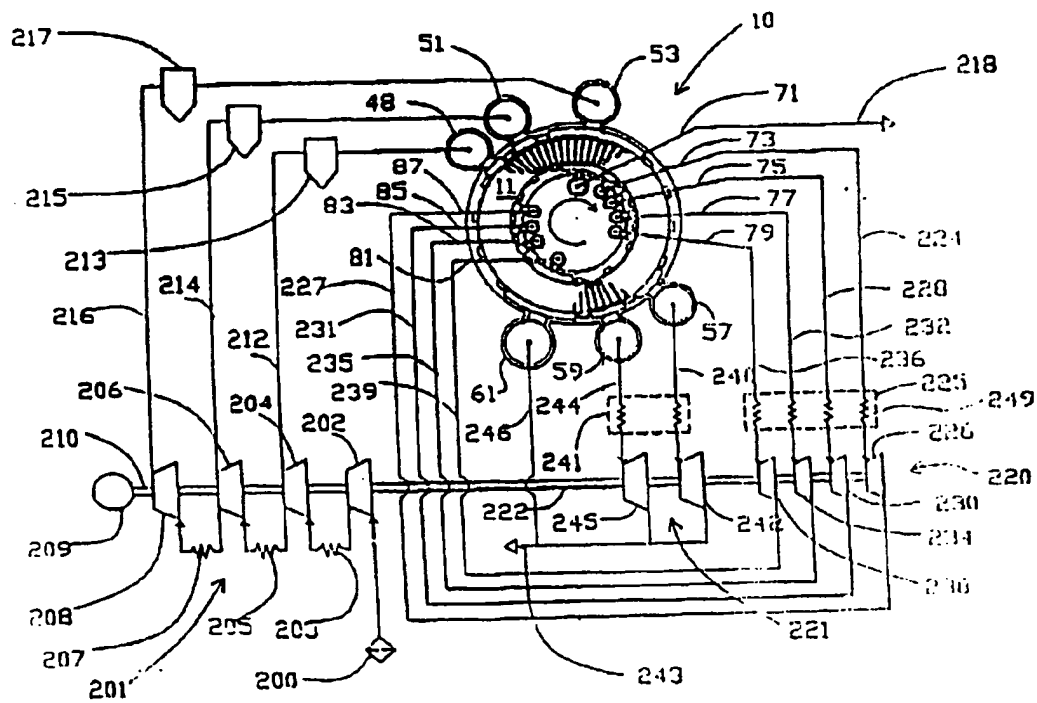


Fig. 7

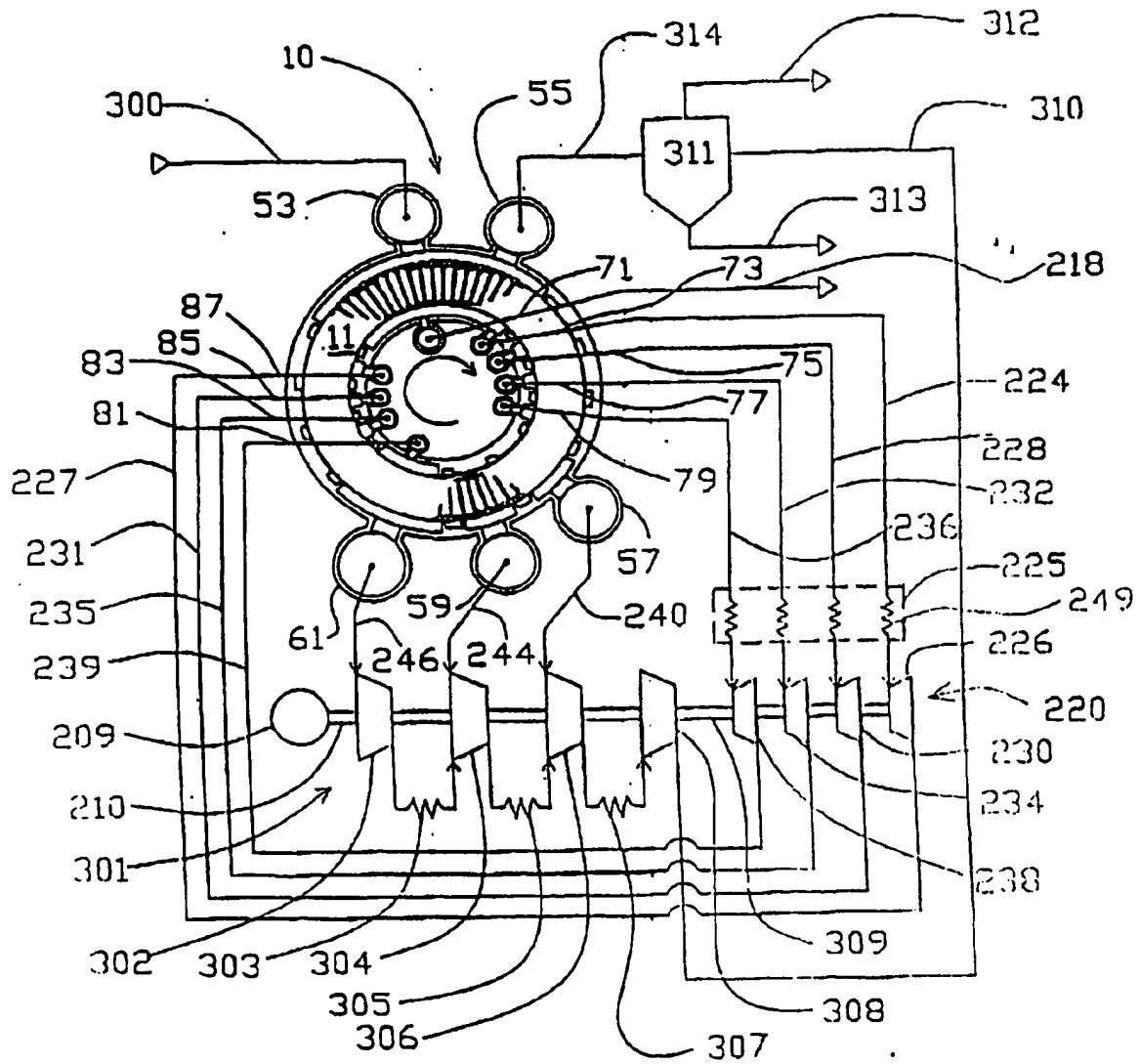
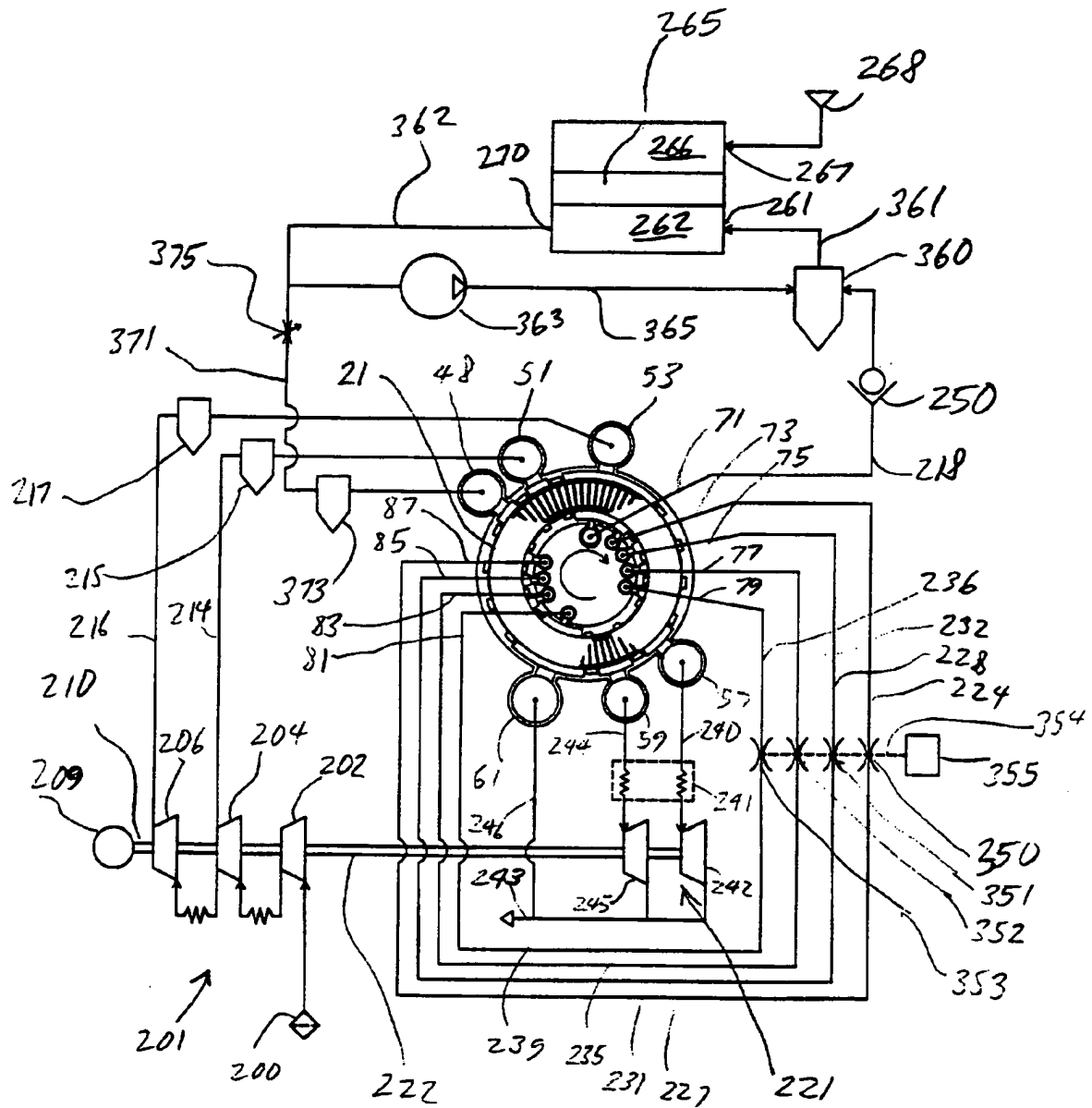


Fig. 8

FIG. 11.



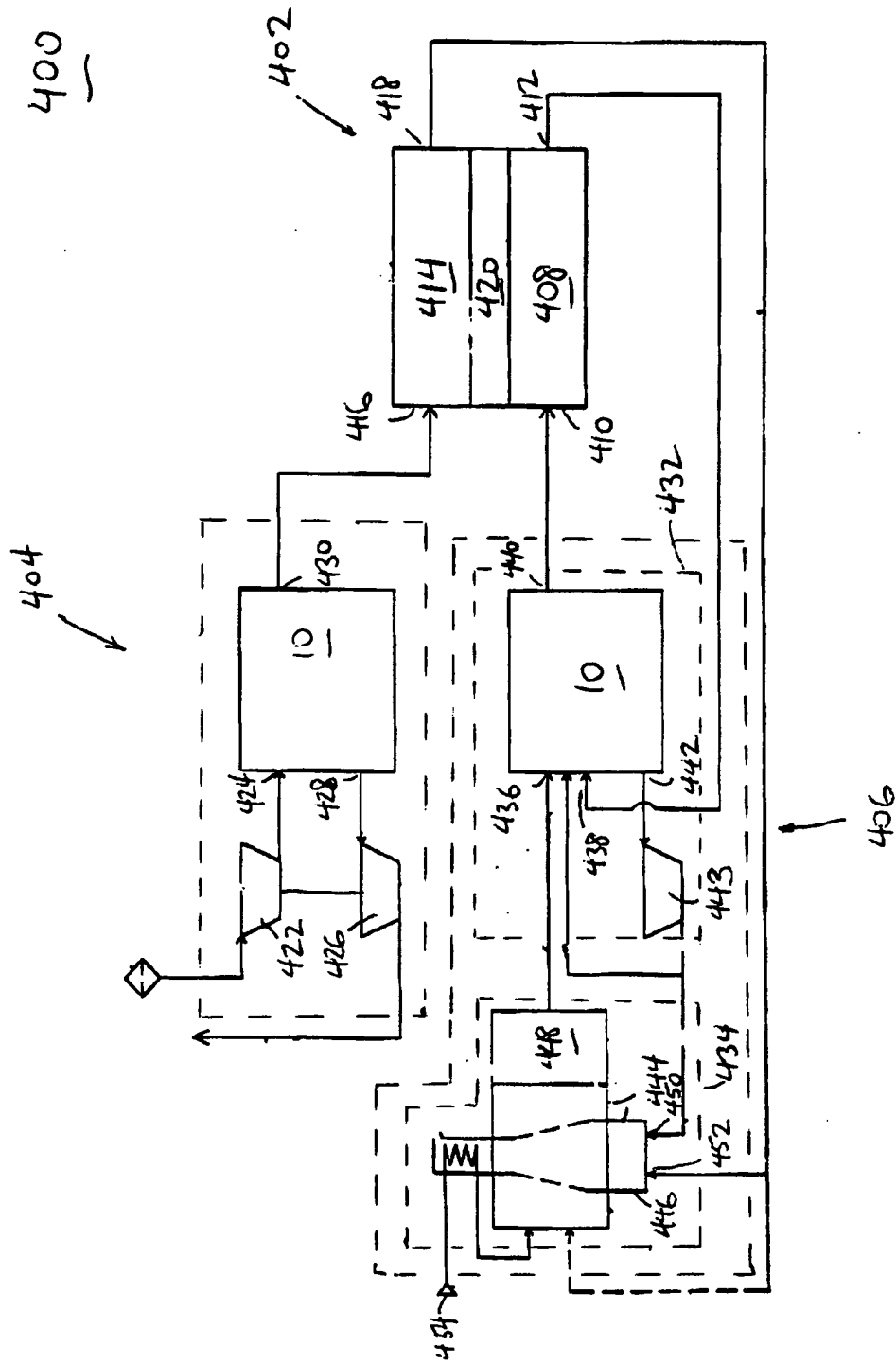


FIG. 12

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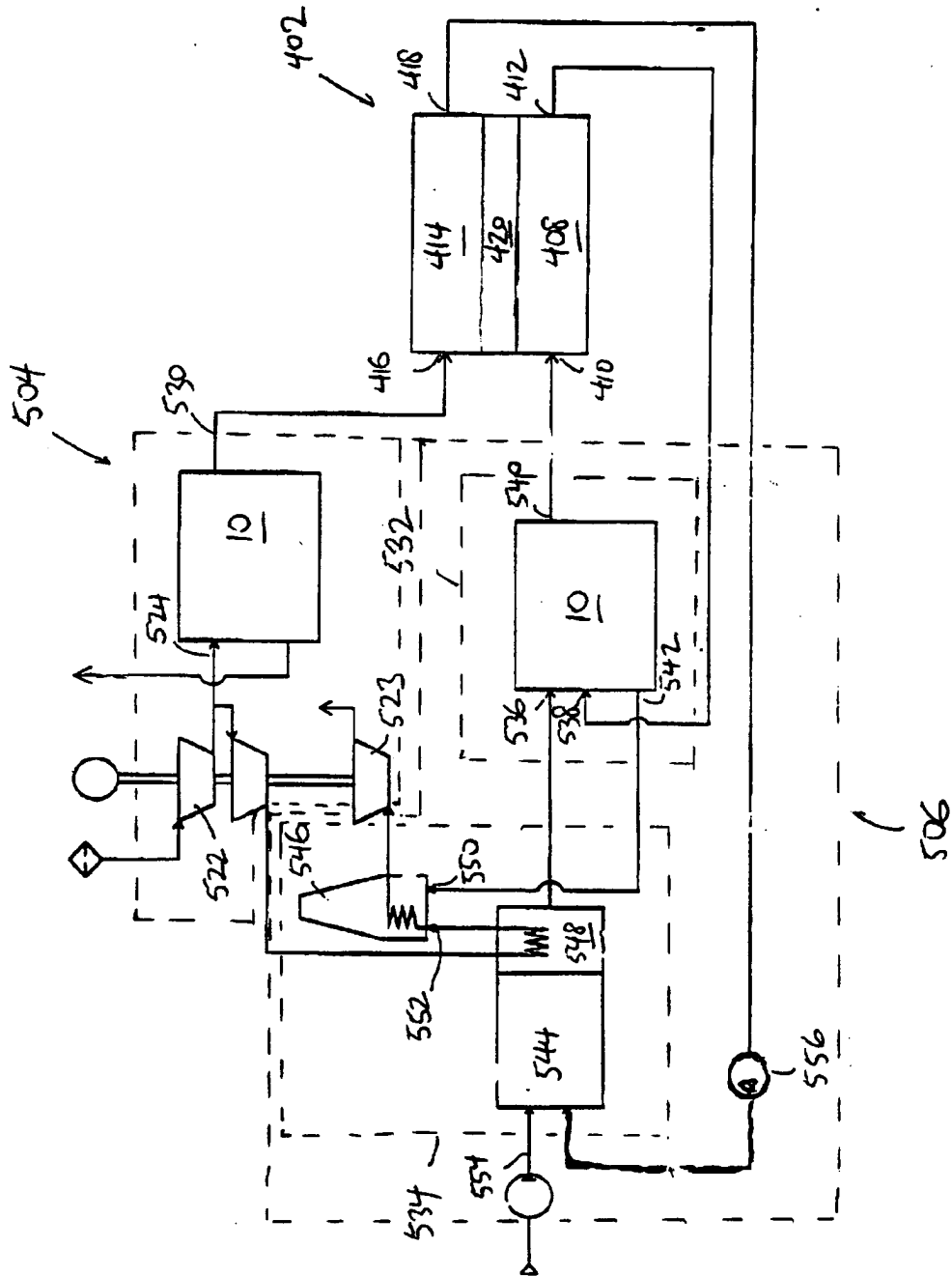


FIG. 13

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